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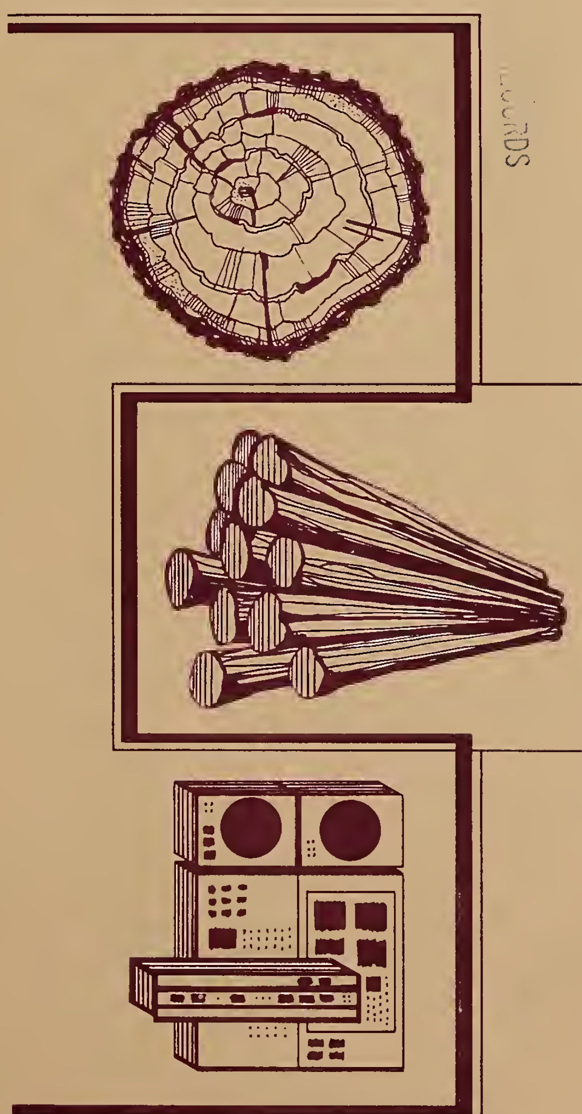
Proceedings— Growth and Yield and Other Mensurational Tricks: A Regional Technical Conference

Logan, Utah, November 6-7, 1984



FOREWORD

This conference was designed to explore current advances in measuring and computing growth, to examine certain modeling systems for determining yield, and to discuss new as well as traditional methods for determining volume. A special attempt was made to relate these ideas to all species of forest trees. Finally, the conference was designed to provide a forum in which practicing foresters could provide comment on the adequacy of current models and methods and describe current needs.

The compilers of this proceedings are deeply grateful to those individuals who prepared and presented the papers published here, and to those individuals whose participation made the conference a success. We acknowledge Ed Harvey and Hank Cheatham, Intermountain Region, Forest Service, for their contributions as part of the program committee. We also express our appreciation to Tom Borg, Program Specialist, Utah State University, for arranging the facilities, and to Reed Christensen, chairman of the Intermountain Society of American Foresters, for supporting this event. A special thank you goes to Karen Charlton who coordinated the preparation of these papers and to Julie Davis and Liz Dailey for their fine production work.

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Proceedings—Growth and Yield and Other Mensurational Tricks: A Regional Technical Conference

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DATA FOR GROWTH AND YIELD MODELS

Robert O. Curtis and David M. Hyink

ABSTRACT: Growth and yield models have a variety of applications, and no one model can best serve all objectives for all conditions. Satisfactory models are dependent on high-quality, consistent data. Data come from some combination of inventory data and research installations. Survey or "growth trend" data provide information on growth now occurring in the present forest; while experimental or "treatment response" data provide information on response to specific treatments applied to defined stand conditions. Cost and the need for program stability and continuity make treatment response studies an activity well suited to regional cooperatives.

INTRODUCTION

Although we are not experts on sampling or inventory, we do know quite an bit about growth and yield modeling and the kind of data it takes to construct satisfactory models. So, we will confine our discussion to data to be used for the specific purpose of growth and yield modeling and, particularly, the relation of permanent plots to this objective.

GROWTH AND YIELD MODELS

"Growth and yield" is a catch-all term that can include anything from inventory updating procedures to quantitative silviculture.

A "growth and yield model" is a system that claims to provide quantitative descriptions of stand development over some range of time, condition, and treatment.

Growth and yield models can serve several purposes, including:

1. Short-term inventory projections.
2. Management planning (land classification, allowable cut, etc.).
3. Evaluation of silvicultural alternatives.
4. Generalized stand management guides.
5. Individual stand management.
6. Quantitative description of growth processes.

Applications differ in required level of detail, flexibility, accuracy, and local specificity. Short-term inventory projections may assume future growth similar to past growth, but long-term estimates must take into account change in condition of the forest and future effects of practices now being applied or anticipated. To evaluate alternatives, we need estimates of results of various possible management regimes. Stand-specific estimates are needed to guide treatment of individual stands. Modeling of growth processes requires extensive biological knowledge in addition to mensurational skill.

Models differ in structure and application. Forests differ in biological characteristics, economic situation, and foreseeable management intensity. People differ in their interests and their view of the future, and they approach growth and yield with different objectives and different viewpoints, shaped by their own background and concerns. It is not surprising, therefore, that we do not have universal agreement on the best type of model, the data needed to construct it, or how best to go about the tasks of data assembly and model construction. There is no reason to suppose that the model and procedures best for one particular set of conditions and objectives will be best for other conditions and uses.

Present models can be crudely divided into two classes: (1) stand models, which use stand average values, and (2) individual tree models, which project individual trees and sum the resulting individual tree estimates to get stand values.

Stand models have the advantages of simplicity and low computing costs, but do not work well for complicated species mixtures and irregular stands. They are most popular in regions where even-aged single species stands are important. Individual tree models are more complex, but can be applied to irregular and mixed-species stands and are favored in regions where this is the predominant condition.

Models, and the computer systems which make them possible, are actively evolving. New questions and new complications are introduced by genetics, wood quality, nutritional and pest management considerations, and other factors. Development of growth and yield systems will be a continuing activity for the foreseeable future.

Paper presented at: Growth and Yield and Other Mensurational Tricks: A Regional Technical Conference, Logan, UT, November 6-7, 1984.

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DATA SOURCES

Models must be based on a combination of biological principles and empirical data. When asked for immediate answers, modelers must make do with whatever data now exist. Unfortunately, models and modelers often seem more plentiful than good data, and good data are critical to satisfactory growth and yield estimates. The basic prerequisite for progress is a data base continuously improving in distribution, quality, and consistency. This must include both inventory data (which describe the existing operational forest) and research data (which describe response to treatment).

Inventories

Forestry organizations conduct periodic inventories to determine volumes and growth rates by administrative units and land condition classes. These inventories generate huge masses of data and at first glance seem the obvious basis for growth models.

Inventories have generally been oriented to estimating present volumes and values, rather than to estimating growth rates and collecting data for modeling purposes. Designs and procedures that provide satisfactory estimates of class means at minimum cost may be quite unsatisfactory as bases for growth and yield models.

The primary relationships in growth and yield models are regressions that estimate rate of change of stand or tree attributes as functions of measured attributes of the present stand (or tree and surrounding stand), including any treatment applied. One seeks estimates of regression coefficients, not class means. This objective requires that conditions influencing growth of the tree or plot be defined as precisely as possible, information that is lacking in most inventories. Small plots subject to large edge effects, ages categorized by broad classes, sketchy height samples, and inaccurate height measurements simply are not good enough. Omission of small trees, common practice in many inventories, produces unacceptable wobbles in growth curves and unpredictable ingrowth.

An inventory designed primarily to estimate present volume and value would concentrate sampling in the old, high-volume stands. Recent inventories with more general objectives often use a systematic grid. But, if we wish to model the forest of the future, we need information on the younger stands and those conditions likely to be important in the new forest. If we wish to compare alternatives, we need to sample different possible stand treatments and regimes. The conditions of greatest interest for future management are usually present in only a small fraction of the existing forest and poorly represented in inventories, or may not be present at all.

Research Studies

Because of the shortcomings of inventory data, much growth and yield modeling has used data collected outside the framework of management inventories. Data have sometimes been collected specifically for modeling purposes; perhaps more often, data have come from installations originally established for related purposes such as thinning and fertilization studies.

PLOT TYPES

Plots (whether fixed area or variable radius) can be classified into three types based on method of growth estimation: (1) single measurement ("temporary"); (2) single measurement with retrospective growth measurements; and (3) remeasured ("permanent").

Single-Measurement Plots

These are one-time measurements of existing conditions, with no direct estimate of growth rate or mortality. The classic example of their use is the normal yield table procedure popular in the 1930's. Such data have very limited usefulness today.

Single-Measurement Plots with Retrospective Growth Measurements

Past growth of surviving trees on plots can be estimated from borings and stem analyses and converted to area estimates using the present stand table. This procedure provides quick growth estimates. It is often used in inventories and can substitute for or supplement remeasured plot procedures. Its principal disadvantages are:

1. Does not give reliable mortality information.
2. Height growth estimates are difficult and expensive (often requiring stem analyses).
3. Past treatment information is usually sketchy or lacking.
4. Does not allow controlled studies of specified treatments.

Despite these weaknesses, the procedure is often useful.

Remeasured ("Permanent") Plots

"Permanent" plots are established at the start of an investigation and then remeasured periodically. An experimental installation may include control plots plus any desired stand treatments, all at the same location.

Such plots are our main source of information on stand response to treatment. They can provide a complete history of stand development and stand treatment, response to treatment, actual damage, and mortality. Development of individual stands and trees can be followed over extended periods

of time and compared with predictions. And the on-the-ground examples and record of treatment and response which they provide are more convincing than any amount of elaborate statistical analysis and model-building. Permanent plots are also expensive, slow to produce results, and require stability and continuity in the research organization.

SAMPLE SELECTION

The first step in sampling is to define the population. In inventories, the population consists of all existing stands, and the primary objective is usually estimation of stratum means.

Things are less straightforward in growth and yield and silvicultural studies, where one seeks information about some largely hypothetical population of possible future managed stands. Here, the primary objective is usually estimation of regression coefficients rather than means.

Yield studies often use regression analyses of unreplicated plots established in portions of the existing forest that meet stated specifications of condition, treatment, and uniformity. Plot location within suitable areas has often been subjective, although an alternative and statistically preferable method is to select and delineate suitable stands and then locate the plot(s) within these by some random or systematic procedure. Deliberate selection of stands to obtain as wide a distribution of selected predictor variables as possible, consistent with objectives and expected application of the model, will provide better estimates of regression coefficients and better predictions near the margins of the data.

In silvicultural experiments, treatments are usually replicated at a given location according to some experimental design. Often, the primary purpose is to test some hypothesis or to define a specific relationship, such as response to fertilizer dosage or density level. Stringent requirements on initial uniformity and comparability of plots within the installation are necessary to minimize the experimental error. This generally requires subjective location of plots, with random assignment of treatments.

Most people recognize that a range of sites, stand conditions, and treatments must be sampled if conclusions from either yield studies or silvicultural experiments are to be generally applicable. It is less generally recognized that data for growth and yield modeling should also include a range over time.

Mortality is often clustered in time and space because of its association with climatic extremes and infrequent events (windstorms, insect and disease outbreaks). Growth of trees can vary widely over periods of a few years because of variation in climatic conditions, sporadic occurrence of widespread stand injuries, and cone crops. Variation with rainfall is particularly pronounced in the semiarid West. It is risky to base estimates of expected growth on measurements made in a single short, and possibly atypical, time period. Short-term variations tend to average out when data represent a series of time periods rather than a single short period. This is one of the advantages of long-term permanent plot observations and accumulation of compatible data over a period of time.

Growth Trend and Treatment Response

It is useful to distinguish two broad classes of data, which we will refer to here as (1) "growth trend" or survey information, and (2) "treatment response" information.

"Growth trend" refers to information on growth now occurring in the existing operational forest under the current type of management. This information comes from inventories or from growth plots that sample existing conditions in the operational forest. It can be used for short-term stand projections, for monitoring development of operationally treated stands, and for adjustment of regional growth models for local use. It can also be used to develop growth and yield models, although it has pronounced limitations. The only conditions sampled are those now existing in the operational forest, and treatment effects are confounded with location. Therefore, such data generally cannot provide quantitative estimates of response to specific treatments. Causal interpretations of regression relationships are uncertain, and one can have little confidence in extrapolations to possible regimes and future conditions different from those which produced the present forest.

"Treatment response" refers to the change in growth which results from a specific treatment applied to a defined stand condition. Good estimates of treatment response are essential to any model that claims to provide quantitative comparisons of the results of possible alternative treatments and management regimes.

To define functional form of relationships, estimate regression coefficients, and identify causal relationships, we need controlled experiments installed for the purpose. These must generally include treatments not now in general use and be designed to produce some stand conditions not now present in the operational forest. As one well-known statistician put it: "To find out what happens to a system when you interfere with it, you have to interfere with it" (Box 1966).

Growth and yield modeling generally involves some combination of inventory and experimental data (Stage 1977). We cannot rely solely on designed experiments, if only because these are and always will be inadequate in number and distribution, particularly for secondary species and mixed stands. But they do provide the best basis for establishing the form of relationships and they are essential for estimating treatment

effects and for predicting conditions and treatment regimes radically different from those present in the existing forest.

Designed experiments have limitations and weaknesses of their own, aside from time and cost. Although they provide reasonable estimates of suppression mortality, they do not provide satisfactory estimates of irregular, pest-induced, or catastrophic mortality. This is true both because of the erratic and clustered distribution of the latter, and because installations must usually be located in stands consciously selected for relative uniformity and freedom from major damage. Such restrictions are necessary if one is to detect treatment effects over background noise; but they also mean that observed growth rates are likely to be somewhat higher than those actually attainable in operational application of similar treatments--the so-called "falldown" effect (Bruce 1977).

This effect is not the only source of bias in models. Incorrectly formulated model components will introduce bias. But even correct formulation and good data do not guarantee unbiased estimates. Somewhere along the line, most of us learned that error in the independent variables biases estimates of regression coefficients. These biased coefficients will still produce unbiased estimates of the dependent variable, _if_ the predictor variables contain errors similar to those in the data used to estimate the coefficients (Draper and Smith 1981).

But growth and yield models are not simple regressions. They are systems of equations in which one regression estimate (which contains error) is used as input to other regression estimates. Estimates are likely to contain unforeseen biases, and it is hard to foresee the net effect. The more accurate our measurements of the basic variables and the better the fit of the component regressions, the smaller these biases are likely to be.

Growth trend data for selected stand categories, obtained from a suitable continuous forest inventory system or randomly or systematically located supplemental growth monitoring plots, are a possible means of identifying and adjusting for such biases. Using growth trend data for stand categories of major interest, it should be possible to compare observed growth with model estimates and arrive at suitable adjustment factors. For such calibration to be feasible, measurement standards must be consistent with those used in treatment response studies.

THE PLACE OF PERMANENT PLOT STUDIES

By now it is probably obvious that we are strong believers in permanent plot studies.

In types such as coast Douglas-fir and the southern pines, thousands of permanent plots have been established over the years. Yet, many people in both the Pacific Northwest and the South see an urgent need for more permanent plot studies. Why?

Sheer quantity means little. Many of these thousands of permanent plot measurements are of very limited value. In part this is due to poor design, poor quality control in field and office, and procedural inconsistencies that make it difficult or impossible to combine data into a common analysis. Only a small proportion of these data apply to those conditions and questions of most importance in evaluating alternatives for the future forest. On the other hand, there are numbers of well-conceived, well-designed, and well-executed permanent plot studies which have been and are invaluable.

Many administrators dislike permanent plot studies. They often fail to grasp the continuing value of well-designed and well-executed studies, but they see clearly the costs and continuing commitment of resources. Conversely, researchers often become attached to their old studies. It is frequently hard to persuade them to junk marginal studies that represent conditions of very limited interest in the future and that were often poorly designed to begin with.

We give here some opinions based on recent discussions among a number of organizations in the coastal Pacific Northwest (University of Washington 1984).

1. In general, new permanent-plot growth and yield installations should be established only as part of a carefully planned series designed to give reasonable coverage of some defined range of site, geography, stand conditions and treatments.
2. Plot procedures and records must be standardized to ensure compatibility of data among installations. Consistency and tight quality control in field and office are absolutely essential.
3. The primary objective should be to produce data suitable for defining response surfaces. Therefore, studies should probably involve minimal replication at each location, but many locations.
4. Each installation should include a basic set of standard treatments common to all locations, while allowing optional additions to this basic set.
5. The basic design should:
    a. Use relatively large plots, which can (1) be continued over a long period of time, (2) provide good diameter distribution data, (3) provide opportunity for subsequent thinning and other stand treatment, and (4) be considered representative of conditions operationally attainable.
    b. Be relatively simple and undemanding in requirements for suitable areas.
    c. Be planned primarily for future pooled analyses, across installations.
6. Effort devoted to species, types, and geographic areas should be related to their long-term importance (acreage and productivity).

7. No one organization can establish and maintain an adequate system of such installations. Cost, and the need for program stability and continuity, make this an activity best suited to regional cooperatives.

SUMMARY

1. There is not and is not likely to be any one growth and yield model that is best for all situations and all applications.
2. Development of growth and yield systems will be a continuing activity for the foreseeable future.
3. Satisfactory growth and yield models are dependent on availability of high-quality data for a wide range of stand conditions and treatments.
4. Data from past conventional inventories have not generally proven suitable for growth and yield modeling.
5. Both survey data and "treatment response" data from designed experiments are needed.
6. Treatment response studies provide the best basis for establishing the form of relationships and are essential for estimation of treatment effects and predictions for conditions and treatments radically different from those present in the existing operational forest. There is a continuing need for such permanent plot studies.
7. New permanent plot studies should generally be established only as part of a carefully planned program. They should be designed with the primary objective of defining response surfaces. Because of costs and the need for stability and continuity, such programs are an activity best suited to regional cooperatives.

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SAMPLING FOR GROWTH ON INDUSTRY LANDS:

OLD-GROWTH VERSUS SECOND-GROWTH CONSIDERATIONS

Steven Kleinschmidt

ABSTRACT: As the forest resource changes, so do needs for growth information. Present needs reflect the transition from the management of existing stands to the management of potential stands. Harvest plans in old-growth forest depended entirely on maintaining a controlled forest inventory of a static resource. Second-growth planning must focus on a dynamic resource and depends on accurate, site-specific stand tables. Old-growth volume estimations do not provide the data necessary for future growth estimation, as do permanent plots stratified by expected future forest characteristics. The factors that define future stand production are site productivity and stand development class. Although this approach is not new, the challenge to foresters is to make it operational.

INTRODUCTION

The emphasis in industrial forest management has been inexorably moving toward second-growth management. Companies either have little old-growth timber remaining or recognize that our survival inevitably depends upon effective management of second-growth.

In response to a changing management and planning environment, a viable inventory system must anticipate and support expanding information needs. Growth data have been regularly collected in industry's controlled forest inventories, but why do we need growth information? Simply, as with all inventory data collection, to provide information for managers to make better decisions. Top management uses this information to project a view of the future forest and the opportunities that this future forest can provide to produce profit. Land managers use similar information to implement the forest objectives on a unit-by-unit basis.

As the resource has shifted from old growth to second growth, the forest objectives and management styles have also changed. For our inventories to be effective in sampling for growth, there must first be an assessment of what growth information is needed and how it will be used by land managers and planners.

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STAND MANAGEMENT

Industrial stand management in the Northern Rocky Mountains is in various stages of evolution from old-growth to residual old-growth to second-growth. This is more than a change from managing old, big trees to young, small trees. The transition involves adopting the philosophy of a timber farmer whose management activities can entirely shape the character of the future crop. It is a primary change from management of the existing standing volume to management of the potential, future volumes (fig. 1).

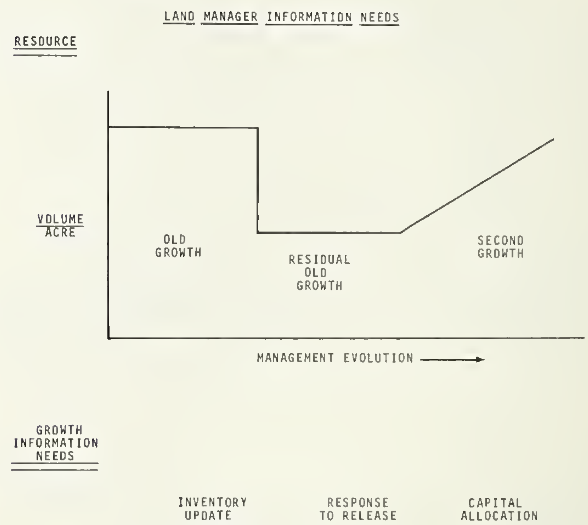

Figure 1.--The land manager's requirements for growth information are changing in response to a changing resource.

Old-growth stands are usually high-volume stands that have had little or no management entries. The resource being managed is the standing volume, and the primary need for growth information is for inventory update to carry the volume forward until the next cyclical inventory. Growth rates are usually low, particularly when increment is compared to the standing volume.

In the Northern Rockies, residual old-growth stands are a mixture of old-growth remnants and submerchantable trees regenerated from the earlier pine and larch sawlog harvests. There may be substantial cubic volume in these stands, though board foot volumes are often low. The growth information needs for these stands are centered on the response to release as the old-growth remnants are removed. Is the understory vigorous enough

to respond, or should it be harvested or slashed and a new stand regenerated? The existing volume and stocking will have an important influence on how this question is answered, but equally important is the stand's potential production.

Second-growth are the stands that are regenerated after the removal of the old growth. They are generally classified into natural and artificial regeneration, thinned and unthinned. The management activities, planting and thinning, that occur early in the life of the stand are the primary influence that will determine future merchantable stand characteristics. The second-growth management considerations are stand establishment and the allocation of capital for intensive stand management. Where can yields be effectively increased through the management activities of planting and thinning? The growth information required for silvicultural capital allocation is potential stand production. As land managers move from an old-growth to second-growth base, the information requirements for existing stand production are being replaced by potential, future stand production. The allocation of scarce capital is the critical decision component.

FOREST PLANNING

Forest management planning has also adapted to the changing character of the forest as we move from a static to a dynamic resource. The development of harvest plans in an old-growth forest depended entirely upon maintaining a controlled forest inventory (fig. 2). The planning needs were effectively served by relatively simple tools such as growth percentages for inventory update-projection and volume regulation formulas for allowable cut calculations. These tools proved useful for old-growth planning because they adequately reflected the overriding importance in stand valuation of the existing volume inventory and the high-valued product revenues.

OLD GROWTH PLANNING SYSTEM

INVENTORY PROJECTION - GROWTH PERCENT

$$V_{t+1} = V_t + GP\ (V_t)$$

ALLOWABLE CUT - VOLUME REGULATION

HANZLIK

$$\text{ANNUAL CUT} = \frac{\text{VOL. OVERMATURE}}{\text{ROTATION}} + \text{INCREMENT}$$

KEMP

$$\text{ANNUAL CUT} = \frac{A_R + 3A_{ss} + 5A_p + 7A_{sw}}{4\ (\text{ROTATION})} + V_{sw}$$

Figure 2.--An example of an old-growth planning system using growth percentages and volume regulation formulas to plan harvests for a high-valued resource.

In second growth the shorter rotation, smaller, more consistent wood determines that stand valuation will no longer be dominated by product revenues, but by operational costs and merchantability specifications. A small change in merchandising specifications can drastically affect the merchantable volume per acre and as a result, impact the per unit costs and wood flows. Examinations of alternative merchantability and cost scenarios in second-growth harvest planning cannot be accomplished with estimates of total strata volume and average costs per unit, but require a linkage between accurate, site-specific stand tables and cost information.

Long-range planning in a second-growth environment requires an increasingly complex forest mosaic of stand development classes. While timber type (species-size class) strata were appropriate in old-growth planning; stand development classes typified by species, size class, site productivity and management activity become crucial to the projection of future inventories. Again, management intervention and potential productivity define second-growth strata. As land managers use potential productivity to define strata for silvicultural capital allocation, planners must also stratify their forest by not only existing conditions, but by anticipated future conditions and the response to these management interventions.

Industrial forest planners have relied on system analysis techniques such as linear programming, dynamic programming, simulation, and network analysis to provide both the flexibility in evaluating alternative cost and merchantability assumptions and the ability to handle large numbers of strata for long-term wood flows (fig. 3).

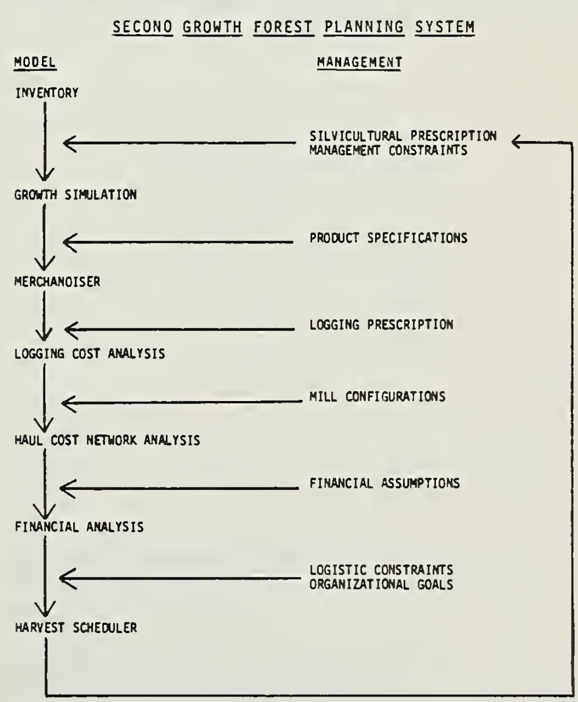

Figure 3.--An example of a second-growth planning system using system analysis to plan harvests for a cost-sensitive resource.

This type of planning model provides a framework for foresters to evaluate the implications of their multiple management and economic assumptions. Moreover, for effective planning, these data-intensive models require future productivity estimates for projecting a large number of diverse stand development classes and refined stand tables for the harvesting of near-term stands. Though outwardly more complex than the old-growth models, the style and structure only reflect the shift from a static, high-volume, high-valued resource to a dynamic, variable-volume, cost-sensitive resource.

INVENTORIES

Management and planning styles are evolving in response to this changing resource and, as a result, the needs for inventory and growth information are also changing. Inventory design must anticipate this evolution if it is to provide useful, timely, management-oriented information.

Old-growth inventory designs have concentrated on the need for estimating total volume. Continuous Forest Inventory (CFI) plots and cyclical temporary plot inventories have traditionally been used to estimate volume. Usually the forest is stratified by timber type, and plots are concentrated in the high-volume strata. The sampling for growth is piggy-backed on this volume estimation sampling design. With an existing, stable, old-growth resource, this strategy provides the information required for inventory updates and planning future harvests.

In second growth, increment is not a secondary information component that can be simply overlayed upon a volume-oriented sample design (fig. 4).

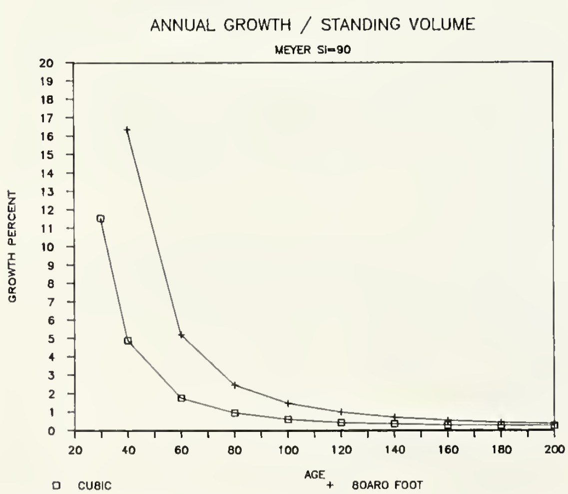

Figure 4.--Annual growth as a percent of standing volume for site index 90 ponderosa pine (Meyer 1938) over a range of stand ages. Growth is a more important stand parameter for shorter rotation, second-growth stands than in old-growth stands.

Growth estimation becomes a more important forest parameter when the large standing volumes are not present, providing an overriding influence on management decisions. When managing the shorter (under 100 years) rotation of second growth, annual increment quickly becomes the dominating influence for projecting future volumes.

The collection of past growth information is of less value in second growth than in the old-growth inventories due to the younger age classes and management intervention. The growth measured from volume inventory plots provides a snapshot of where a stand has been but not where it is going. With rapidly changing growth rates in stands less than 100 years old, extrapolation of past growth could easily underestimate future production, resulting in foregone capital investment opportunities or overestimate, resulting in excessive future wood supply projections (fig. 5). In addition, pretreatment growth rates will hopefully have little correlation with posttreatment response to density control. While growth is a minor and consistent component in old-growth projections, it is a primary but variable component for second-growth projection. By necessity, the standing volume estimation should be divorced from the future growth estimation.

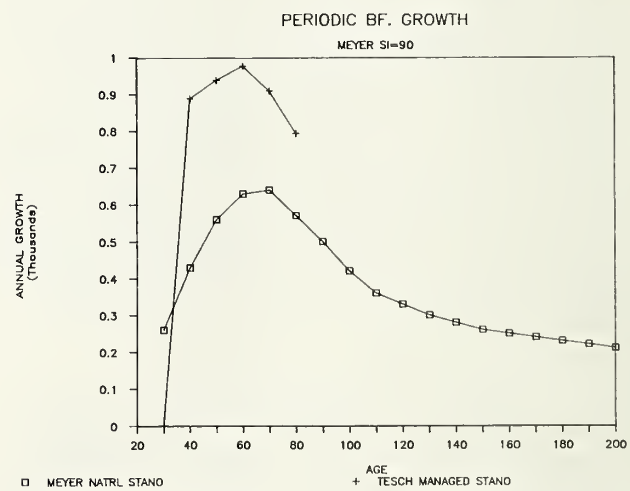

Figure 5.--Periodic board foot growth over a range of stand ages for a natural stand (Meyer 1938) and a managed stand (Tesch 1980). Growth rates are rapidly changing and less predictable for second-growth stands due to shorter rotation and a range of management activities.

Caught in the middle between demands for site-specific stand tables and the need for alternative sampling approaches for future growth estimation is the inventory forester with a fixed budget. It is possible to meet these increasing information demands, but only if sampling strategies are targeted specifically toward collecting only the pertinent information required for that phase of the inventory.

The conventional inventory must concentrate on the information needs from the existing stand, such as stand tables and management objectives and constraints. These data can be collected within a design using a mixture of volume point sample plots and fixed radius regeneration plots. To efficiently achieve the increased sample intensity inherent to site-specific inventories, the management unit inventory should concentrate on the estimation of site productivity and stand development class. Site productivity can be estimated from measured site trees or site characteristics such as slope, aspect, habitat type, and soil type. Stand development class can be defined by stand structure and management strategy. By limiting the management unit inventory to a basic cruise, considerable efficiency can be gained in order to keep a site-specific inventory of second growth up to date. Growth can be measured on these plots for an index of vigor, but only a subsample would be needed. Alternative measures such as crown ratio provide vigor information and can be collected more quickly.

GROWTH INVENTORY

Primary increment information for second-growth stands should be sampled using a design that provides future growth information. A viable approach to this problem is a permanent plot system stratified by expected future forest characteristics.

Permanent plots are irreplaceable for second-growth information needs as long-term response to silvicultural treatments can be tracked. Crucial components of growth, such as height growth and mortality, can only be reasonably monitored on permanent plots. Old-growth could be efficiently managed with the assumption of little to no height growth, but the capability of a stand to reach merchandising specifications at 16 or 32 feet will be vital in the development of a management plan. Mortality, always the bugaboo for mensurationists, can readily be measured and evaluated for causal factors on permanent plots.

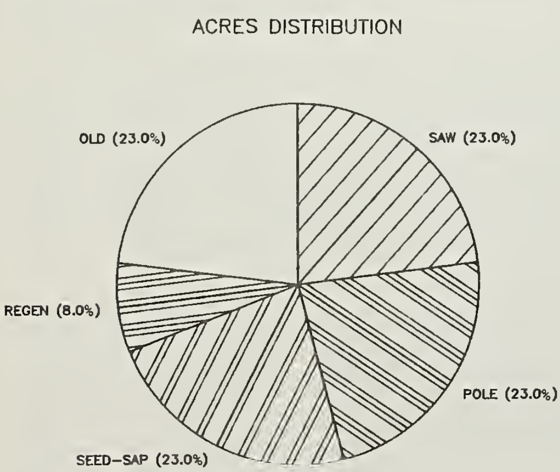

Figure 6.--A representation of a hypothetical forest managed under acreage control.

Stratification in sampling growth should be oriented toward providing information on future, potential production. Therefore, the forest should be stratified not by existing stand conditions, but by future stand conditions and future production. For a hypothetical forest with acres equally distributed over size classes (fig. 6), alternative views of the forest are presented for volume and growth estimation (fig. 7). By evaluating the resource using future stand conditions and production, you will arrive at an entirely different view of your forest and an entirely different sampling strategy from that of the volume inventory. Greater emphasis is placed upon stands that are entering the higher productivity classes. Pole and seedling-sapling stands, thinned, and planted stands will have a greater weighting due to their higher production.

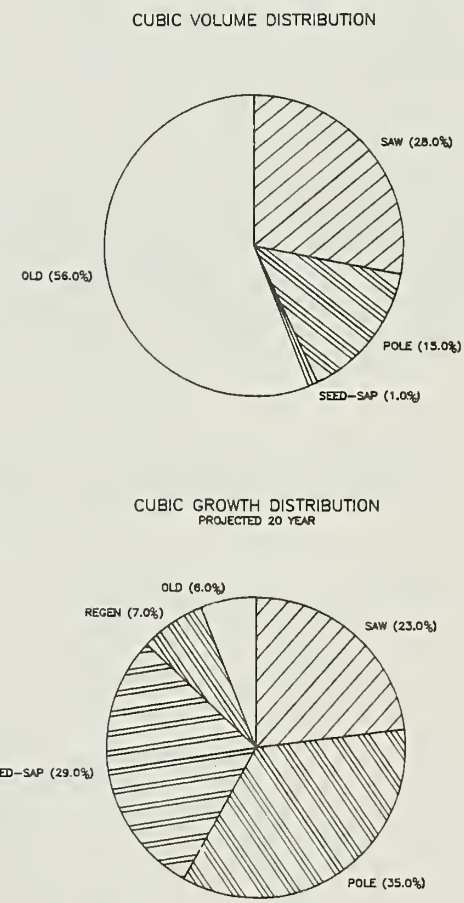

Figure 7.--Alternative views of the same forest depending upon whether cubic volume or cubic growth is the forest parameter to be sampled.

The factors, previously identified, that define future stand production are site productivity and stand development class. Stand development classes have been referred to throughout to stratify inventory and growth populations for the second-growth forests. This classification provides the flexibility to consider existing stand conditions and also include expected future development. In industrial forestry, silvicultural intervention leaves a significant imprint on the

future forest and must be included in any stratification; however, each organization must assess the factors that will determine the characteristics of its own future resource.

The evaluation of future stand conditions, though difficult, can be a creative management assessment of the direction that the forest is headed. This implies that the stratification does not remain static with the initial growth plot establishment but must be periodically assessed. This type of assessment can only be healthy for an organization.

To apply the information from the growth inventory system, continuous managed stand growth and yield tables can be produced using either conventional empirical yield summaries or computer-based variable density yield table generators. The periodic remeasurement and establishment of plots in new strata provide an ongoing, continuous data base for growth and yield table recalibration. To estimate existing and potential forest production, the inventory cruises supply the site and stand development classifications for entry into the growth and yield tables.

Proposing to measure growth on permanent plots stratified by conditions that will exist in the future forest is nothing new. Research foresters have consistently used this approach. The challenge is to take this research approach and make it operational. Nearly all forest management companies in the Northern Rockies use local growth and yield information to project future stands for management and planning purposes. The continual recalibration of local growth and yield tables is no longer a research activity, but is an ongoing activity for a forward-looking, operational inventory.

The sampling strategy for estimating increment in industrial second-growth forests may not be readily applicable to all organizations; however, certain common factors exist in developing a sampling strategy. For information to be useful and timely, it is imperative that form follows function. This requires an inventory design based on a thorough assessment of the resource and an evaluation of the present and projected user information needs. Against a clearly defined picture of management information needs, alternative sampling systems can be evaluated for efficiency, timeliness of information delivery, and level of detail for today's and tomorrow's inventory.

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CALCULATING GROWTH FROM VARIABLE PLOTS:

ARE WE FITTING SQUARE PEGS INTO ROUND HOLES?

Charles J. Chambers, Jr.

ABSTRACT: Good documentation of the theory, development, and use of variable plot sampling dates back to 1952. Many foresters look upon the growth components of fixed plots as different than those of variable plots. In fact, they are not. Ongrowth trees, "the square peg," are handled differently in two common methods of variable plot growth calculations. Both are correct, but both sometimes produce confusing results. In the "Bitterlich method," growth equals measurement 2 minus measurement 1, but very erratic growth estimates occur (high variance); the "Beers method" causes a more realistic growth estimate, but growth is not equal to measurement 2 minus measurement 1. Both methods will give statistically similar answers, but the Bitterlich method will vary the most. Approaches have been developed that make volume and growth estimates compatible with greatly reduced variances. The use of variable plots for growth causes no real problems that do not also show up in fixed plots.

INTRODUCTION

The concept of variable plot sampling was first reported by an Austrian forester, Dr. Walter Bitterlich, in 1948. About 5 years later, Grosenbaugh (1952) introduced the concept in the United States; he extended it to the estimation of volume, number of trees, and so on, and developed a sound theoretical basis for it. Many universities and agencies conducted research to refine and develop the theoretical and practical aspects of the system, but it took about 10 to 15 years before the American forester began to appreciate the new system and use it in estimating timber volumes.

The theory, development, and use of variable plot sampling has been well documented in publications that date back to 1952. I assume that most of you are familiar enough with variable plots to permit us to move right into the main subject of growth using variable plots. For a review or a first exposure, I recommend Grosenbaugh (1958), Bruce (1961), Beers and Miller (1964), and Husch and others (1972). Literature bibliographies are available from Thompson and Deitschman (1959) and La Bau (1967).

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Although foresters now use the variable plot system for timber inventory and cruising, many have hesitated to use it for permanent plots for research or CFI uses. The idea of using a variable plot system for growth estimations resembled making square pegs fit into round holes in that the system seemed totally inappropriate for obtaining the desired data. This paper will focus on making the reader see that, in fact, the "square" peg always was round. The important point is that "variable plots" means that they vary in size when established, not that they vary over time. In support of using a variable plot system for growth estimates, I will conclude with a brief review of how the Washington State Department of Natural Resources has used a variable plot system for growth and yield information.

GROWTH COMPONENTS

Many foresters look upon the growth components of fixed plots as different than those of variable plots. In fact, they are not. Growth components of both are:

1. Survivor trees (trees that were measured in period 1 and then remeasured in period 2)
2. Cut and mortality trees
3. Ingrowth trees
4. Ongrowth (the square peg)

Calculating the growth of survivor trees for fixed plots and variable plots is straightforward and can be handled similarly. The problems of handling ingrowth trees are also the same for fixed and variable plots. Ingrowth is defined as trees not previously large enough to be included by the inventory specifications and which "suddenly appear" on the fixed plot or variable plot once they are of merchantable size. In the variable plot system, each tree represents the same basal area as any other tree, regardless of size. Consequently, the effect of ingrowth is even greater when it does occur, although it occurs less frequently on variable plots. This form of sudden change is generally tolerated in both sampling systems. (Iles and Beers 1983). The most promising current tactic in Iles' opinion (1981) is to establish a sufficiently large minimum plot size for small trees.

The Washington State Department of Natural Resources has included all trees 1.5 inches and larger to reduce, but not totally solve, the problem of ingrowth. The sudden loss due to mortality or harvest remains a major problem for both fixed and variable plots. It is the one problem which seems to lack a practical solution in either system at the present time (Iles 1981). The last component of growth is the "ongrowth trees," the square peg in the eyes of many that is the focus for the remainder of this paper. Briefly, ongrowth trees are those not included in the sample on the first measurement, even though of merchantable size, but that are included in a subsequent measurement. How these trees are handled in growth calculations will be discussed later, and the definition of ongrowth should be kept in mind.

PLOT SIZE CHANGES

What is happening with ongrowth trees also occurs with fixed plots when plot size changes. Let's say we have a 10-year-old Douglas-fir stand. We establish a 1/40-acre fixed plot, and a total of 10 trees are on the plot. The object of the inventory is to maintain at least 10 trees for measurements over time. As the years go on, thinning takes place and soon only five trees remain. The forester therefore doubles the size of the plot, and creates a larger plot with a new combination of trees. New estimates for the stand may be quite different than for the old 1/40-acre plot. The same thing happens each time he returns to his variable plot if he checks for ongrowth trees with his prism; basically he changes the size of the plot and creates a new combination of trees. This problem thus shows up in both systems.

Traditionally, fixed plots never seem to be measured long enough to require changing plot size in order to achieve plot efficiency. (Plot efficiency is defined as maintaining enough trees on a series of plots to keep the variation to a minimum. In a series of 1/40-acre plots with one tree per plot, the variation would be high. If the plots are 1/2 acre with many trees per plot, the variations would be markedly reduced. Some combination of a small variance and dollars spent must be considered in plot efficiency.) On the other hand, with variable plots inventory foresters feel they need to check for ongrowth trees at each measurement. This check is probably not necessary, and the efficiency of a variable plot could last over a number of remeasurements.

What seems to bother almost everyone dealing with growth is the typical printout of a remeasurement of a variable plot where ongrowth trees have been noted (table 1).

Table 1.--Typical basal area growth (ft^2) on variable plots with and without ongrowth trees

Plot	Measurement 1	Measurement 2	Ongrowth trees	Growth
1	40	60	Yes	7.7
2	60	60	No	6.8

CALCULATION PROBLEMS

Why does 60-40 show a growth of 7.7 ft^2 on plot 1, and 60-60 a growth of 6.8 ft^2 on plot 2? An understanding of the two ways growth can be calculated on variable plots is needed to clear up the confusion. The first of the two methods I will call the "Bitterlich" method. (This does not imply that Bitterlich advocates the method, just that it was one of the earliest attempts and therefore became associated with him.) This method calculates the growth estimate as the difference in successive estimates from one period to another. This sudden change of growth caused by the ongrowth tree makes the operational forester uneasy because of the large variance in growth. Using a five-plot example, the principle and large variances of the method are illustrated (table 2).

Table 2.--Growth calculations by the Bitterlich method

	Measurement 1	Measurement 2		
Plot		Survivor	Ongrowth (OG)	Totals
	------------Basal area per acre, ft^2------------			
1	40	40	20	60
2	60	60	0	60
3	140	140	0	140
4	110	110	10	120
5	120	120	30	150
Total	470	470	60	530

Growth = (Survivor basal area + ongrowth) - Measurement 1

60 = 530 - 470

We now recognize two conditions of the Bitterlich method:

1. Growth = measurement 2 - measurement 1, and
2. Very erratic growth estimates (high variance) per plot occur as shown in table 2. This would be the same for fixed plots if recalibration takes place (change in plot size).

To make the square peg round and get away from erratic growth, Beers (1964) and earlier Grosenbaugh (1958) introduced a system in which the estimates of basal area and basal area growth are independent of each other. Initial basal area is estimated using Bitterlich's estimator or some alternative estimator. The growth estimate is usually based on trees included in the initial measurement, and the ongrowth trees are not considered. Although Beers shows the ongrowth trees in his tables, he does not recommend they be used. In fact, ongrowth trees (which is a recalibration of plot size) should only be taken when the plots become inefficient. Forget them! Table 3 illustrates our first example (table 1, plot 1) in more detail.

Table 3.--Comparison of growth methods

Measurement 1				Measurement 2		
D.b.h. (D1)	Basal area (BA1)	Trees per Acre (T/A1)		D.b.h. (D2)	Bitterlich Basal Area (BA2)	Beers Basal Area
10	20	36.7	Survivor trees	11	20	24.2
12	20	25.5		13	20	23.5
			Ongrowth trees	14	20	--
Totals 40		72.2			60	47.7

Bitterlich Growth: BA2 - BA1 = 60 - 40 = 20 ft².

Beers Growth: (T/A1 * ($D2^2$ * 0.005454)) sum for all trees - BA1 = 47.7 - 40 = 7.7 ft².

Now we have a situation of more realistic growth estimations per plot, but:

Growth ≠ measurement 2 - measurement 1

7.7 ≠ 60 - 40

Bitterlich's method bothers some because growth is too variable. Beers' is consistent, but it bothers others because it doesn't add up.

Which of the two is better? Well, this depends on the user. Flewelling (1981) goes into more detail in his comparison of each method. (I should point out that Flewelling uses different nomenclature than I have used. He refers to the Bitterlich method as compatible and Beers' method as noncompatible.)

Looking back at table 1, the confusion comes about because the example is mixing the two methods. The user is confused because of the noncompatibility, that is, measurement 2 ≠ measurement 1 + growth.

In other words, select one method and stay with it, or show both growth estimations for each plot and total.

In summary, the Bitterlich estimate associated with the usual basal area estimator has a high variance; Beers' method with less variance is usually preferred, but both are unbiased. In other words, if "x" number of plots is analyzed, both methods give statistically similar answers, but the Bitterlich method would vary the most.

IMPROVED METHODS

Can anything be done to cause less variance in growth and measurement 2 to equal measurement 1 + growth? In other words, can the best of both worlds be reached? Two recent approaches enable us to achieve these ends. Iles (1979), Iles and Beers (1983), and Flewelling (1981) introduced methods to solve the problem of large and sudden changes. They modify "the shape of the estimate" over the plot area surrounding the tree and into which the sample plot might fall. In a nutshell, what they are saying is to only account for the shell of additional wood that is put on between measurement 1 and measurement 2 as growth. Their approaches have several advantages (Iles and Beers 1983). They are:

1. Volume and growth estimates are "compatible" with a much reduced variance (growth = measurement 2 - measurement 1).

2. Volume estimates change slowly and consistently as the plot size changes.

3. Method can be applied to plots already measured if the distance to the trees is known.

Additional discussion is available in Iles' and Flewelling's papers.

DON'T CHANGE SIZE

In conclusion, the substitution of variable plots for permanent plots causes no problems that do not show up in fixed plots. They are not noticed in fixed plots because we changed the size infrequently. The solution is the same in both cases: don't change the plot size. The big advantage of variable plots over fixed plots is the cost-efficient estimates of volume or growth or both. Ingrowth trees have the same problem for both variable plots and fixed plots. A sudden loss of trees remains a problem in both. Survivor trees are handled the same. The "compatibility" question only arises when recalibration takes place. This too can be taken care of by using Iles' or Flewelling's approaches.

In practice, the Washington State Department of Natural Resources has been using the variable plots system since 1957, when the original inventory was established. Nine years later, 3,500 variable plots were established for growth and yield. By 1980 the Division of Timber Sales started cruising using the variable plots system. Flewelling told us (1981) "of the many organizations I have contacted, you have maintained the best records and are probably making the best use of your growth data."

One use of the data was the development of a basal area growth equation which was used to derive growth tables for Douglas-fir (*Pseudotsuga menziesii*) (Chambers 1980) now being used in the Pacific Northwest. This procedure was later described by Clutter (1983) as an acceptable means to predict future yields using a basal area growth equation derived from variable plots. Last, but not least, we are now developing growth estimations from the department's 2,500 variable plots in eastern Washington for the allowable cut calculation.

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SQUARE PEGS AND ROUND HOLES: PROCEED ONLY WITH CAUTION

Roger C. Chapman

ABSTRACT: Estimation of stand growth from variable radius plots has been the subject of some misunderstanding among foresters. Grosenbaugh in 1958 and Beers and Miller in 1964 identified the phenomenon of "ongrowth" and suggested procedures for estimating growth from remeasured points. Several methods have been suggested for estimating growth using diameter increment cores and temporary variable plots. Using the basic probabilistic concepts of PPS sampling, it is shown that a choice of basal area is a critical element in estimating and interpreting tree and stand growth when one is using either temporary or remeasured points.

INTRODUCTION

The use of probability proportional to size (PPS) sampling to estimate stand growth often has been debated among foresters. In the subsequent paragraphs some of the probabilistic elements of PPS sampling which are associated with stand growth estimation are discussed. The focus is on the probabilistic structure of the Grosenbaugh (1958), Beers and Myers (1964) stand growth estimators and procedures. Those readers interested in the variance characteristics of stand growth estimators or ongrowth are directed to Flewelling (1981), Martin (1982), and Flewelling and Thomas (1984).

In the search for computationally efficient estimators, we often forget that the individual tree's probability of being sampled is an essential element in PPS sampling. The probabilistic aspects of PPS sampling are particularly important when variable plot data are used to estimate stand growth.

The probability that a given tree will be sampled in a 1-acre forest with a single randomly located point is

$$p = \frac{\text{area of tree's projected circle (ft}^2\text{)}}{43560}$$

$$= \frac{\text{tree basal area (ft}^2\text{)}}{\text{BAF}}$$

$$= 1/\text{STF}$$

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where STF is the stand table factor associated with the given tree and basal area factor, and BAF is the basal area factor.

The general formula for estimating the per acre value of any tree characteristic y_j--is

$$\hat{Y}_a = [1/n] \sum_i^n \sum_j^{m_i} [y_{ij}/p_{ij}]$$

or alternatively

$$\hat{Y}_a = [1/n] \sum_i^n \sum_j^{m_i} [STF_{ij}*y_{ij}]$$

where

n = the number of points sampled,

p_{ij} = the probability of the jth tree on the ith point being sampled,

STF_{ij} = the number of trees per acre represented by the jth in tree on the ith point,

m_i = the number of "in" trees at the ith point, and

Y_{ij} = the characteristic of interest on the jth tree on the ith point.

PROBABILITY, GROWTH, AND TREE SELECTION

In developing sampling techniques to accurately and precisely estimate stand growth it is necessary not only to state whether one is estimating past growth or predicting future growth but also to carefully define the type of growth (net, gross, with or without ingrowth and/or mortality), and cut that is to be estimated.

Obviously when trees are sampled proportionally to their size, the probability of a tree being sampled increases with time. In a 1-acre forest the probability of initially sampling a tree of diameter d with a single randomly located point is

$$p_1 = 0.005454\ d^2/\text{BAF}.$$

After n years and diameter increment Δ the probability of sampling the tree with a single randomly located point becomes

$$p_2 = 0.005454\ [d + \Delta]^2/\text{BAF}.$$

The relative change in the probability of selection, p_2/p_1, associated with a given diameter increment Δ is

$$p_2/p_1 = [1 + \Delta/d]^2,$$

$$= STF_1/STF_2.$$

The change in the probability of selection is not only a function of the diameter increment occurring during the period but also of the initial diameter. For a given diameter increment the relative change in the probabilities of selection, p_2/p_1, declines as diameter increases.

The changes in the probabilities of selection associated with a range of diameters and with specified diameter increments are shown in figure 1.

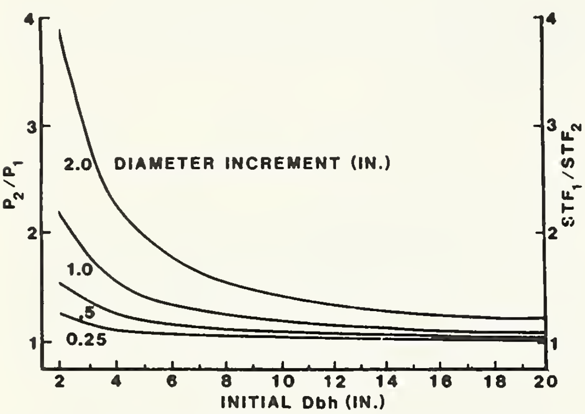

Figure 1. --Changes in probabilities of selection associated with range of diameters and specified diameter increments.

Stand growth can be estimated from remeasured plots or from temporary points if additional growth information is collected. The subsequent paragraphs describe the estimation of growth from remeasured and temporary points.

ESTIMATED GROWTH FROM REMEASURED POINTS

Grosenbaugh (1958) and Beers and Miller (1964) advocated using only trees that were "in" at the beginning of the measurement period to estimate stand growth when remeasured points were being used. In constructing growth estimators, they used the probabilities associated with the diameter when trees were first of merchantable size. For trees of merchantable size and "in" at the beginning of the measurement period, the probability p_{ij} associated with the initial diameter $d_{1_{ij}}$ was used. For trees of less than merchantable size but "in" at time of first measurement and growing into merchantable size during the remeasurement period, the probability $p_{2_{ij}}$ associated with the diameter at the end of the period, $d_{2_{ij}}$, was used. Their estimator of per acre volume growth is

$$\hat{vg}_a = 1/n \sum_i^n \sum_j^{m_i} [(1/p_{1_{ij}}) * gv_{ij}] + [(1/p_{ij}) * gv_{ij}]$$

$$= [1/n] \sum_i^n \sum_j^{m_i} [STF_{1_{ij}} * gv_{ij}] + [STF_{2_{ij}} * gv_{ij}]$$

where

$$gv_{ij} = [V_{2_{ij}} - V_{1_{ij}}],$$

$V_{1_{ij}}$ = the volume at the beginning of the measurement period of the jth tree on the ith point,

$V_{2_{ij}}$ = the volume at the end of the measurement period of the jth tree on the ith point,

$p_{1_{ij}}$ = the probability of selecting the jth tree on the ith point at the beginning of the time interval, and

$STF_{1_{ij}}$ = the stand table factor of the jth tree on the ith point at the beginning of the remeasurement period.

Ongrowth trees, trees originally classified as "out" but which grew sufficiently to be "in" at time of remeasurement, are ignored in Grosenbaugh's and Beers and Miller's estimates of stand growth. Inclusion of ongrowth trees in the growth estimators not only increases the estimated growth but also usually inflates the standard errors associated with the growth estimates.

Myers and Beers (1968) compared the average annual basal area ingrowth per acre obtained from 0.2-acre plots in Wisconsin with estimates obtained from PPS sampling when (1) ongrowth trees were ignored, (2) basal area on ongrowth trees was included with ingrowth, and (3) basal area growth of ongrowth trees was included from the time they qualified for the sample. The results of their study are summarized in figure 2.

ESTIMATING GROWTH FROM TEMPORARY POINTS

In estimating stand growth from temporary points, one must decide whether one wishes to mimic the type of stand growth estimates obtained from remeasured points or to estimate the past stand growth of surviving trees.

When temporary points are used to mimic or supplement remeasured points all tallied trees should be increment bored (Grosenbaugh 1958) in order to determine the status of the tallied trees at the beginning of the measurement period.

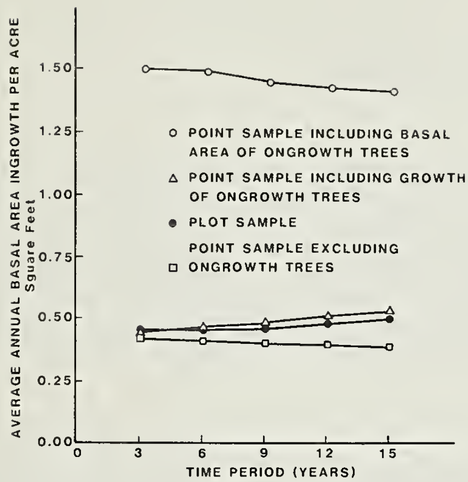

Figure 2.--Average annual basal area ingrowth per-acre estimates for various time periods. (Myers and Beers 1968)

The diameters are backed up to the beginning of the growth period and only trees "in" at the beginning of measurement period are used in the Grosenbaugh, Beers, and Miller-type stand growth estimator:

$$\hat{g}_{1_a} = [1/n] \sum_i \sum_j (1/p_{1_{ij}}) * g_{ij} \sum_i \sum_j (1/p_{2_{ij}}) * g_{ij}$$

"in" merchantable trees + ingrowth

$$= [1/n] \sum_i \sum_j STF_{1_{ij}} * g_{ij} + \sum_i \sum_j STF_{2_{ij}} * g_{ij}.$$

where

g_{ij} = is the growth of the jth tree on the ith point during the remeasurement period. The estimate of growth per acre based on the basal area at time of point establishment (after growth has occurred) is

$$\hat{g}_{2_a} = [1/n] \sum_i \sum_j (1/p_{2_{ij}})\, g_{ij} \quad \text{. . . "in trees"}$$

$$+ [1/n] \sum_i \sum_j (1/p_{2_{ij}})\, g_{ij} \quad \text{. . . ingrowth}$$

$$+ [\text{ongrowth}]$$

$$= [1/n] \sum_i \sum_j STF_{2_{ij}} * g_{ij}$$

$$+ [1/n] \sum_i \sum_j STF_{2_{ij}} * g_{ij} + \{\text{ongrowth}\}$$

where $\hat{g}_{2_a}$ is the average growth per acre experienced by survivors during the previous remeasurement period. If no ingrowth or mortality occurs in the immediate future and if the growth rate is the same as in the immediate past, $\hat{g}_{2_a}$ is a reasonable estimator of future stand growth.

Since $STF_{2_{ij}} < STF_{1_{ij}}$, it is obvious that the growth estimate $\hat{g}_{2_a}$ derived from "in" trees using the basal area at time of point establishment and the associated stand table factors $STF_{2_{ij}}$ will be less than the growth estimate $\hat{g}_{1_a}$ based on the diameters at the beginning of the period of measurement. The magnitude of the differences between STF_1 and STF_2 associated with a range of diameters and diameter increments is shown in figure 1. For example, for a 9-inch diameter tree with a diameter increment of 2 inches in the measurement period, STF_1 is 1.5 times greater than the STF_2 associated with its diameter at the end of the period. The tree's contribution to growth per acre based on the initial diameter is thus 1.5 times greater than its contribution would be if the final diameter is used. For older forests having large-diameter trees and relatively small-diameter increments, the difference between $STF_{2_{ij}}$ and $STF_{1_{ij}}$ will tend to be small. The inclusion of ongrowth complicates the comparison of the estimators $\hat{g}_{1_a}$ and $\hat{g}_{2_a}$.

If one wishes to augment a set of permanent growth points with growth data from temporary points, it is essential that the two sets of data share the same time frame. Combining growth estimates based on different time frames will provide results of questionable value.

CONCLUSIONS

A review of the literature addressing the problem of estimating stand growth from PPS sampling data indicates (1) that stand growth can be estimated with PPS sampling and (2) that the problem is complex. The problem of estimating stand growth with PPS sampling revolves around the structure of the estimator to be used and the treatment of sample trees, most notably ongrowth. It has been shown that the choice of the probabilistic structure, the stand table factors chosen, is critical. Foresters using PPS sampling for the first time to estimate stand growth should (1) review the literature to obtain an estimator whose statistical properties are known, at least to some extent, and (2) be sure they understand which population parameter they are estimating. Foresters already using PPS sampling to estimate stand growth should review the field procedures and the estimators being used to ascertain whether their current procedures and estimators are appropriate.

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GROWTH FROM VARIABLE PLOTS: WHO CARES?

John L. Teply

ABSTRACT: Although growth estimates are an important aspect of forest management, too often growth is viewed as an isolated factor, not as one of several factors affecting change. The critical question should be rephrased from "What is the volume and growth?" to "What is the volume and how has it changed?" Effective management decisions cannot be made with growth data alone.

INTRODUCTION

So far this morning, this panel has presented a wide range of concerns dealing with growth from variable plots. These concerns have revolved around the strengths and weaknesses of sampling for growth using such plots, as well as very technical aspects. By simply considering the discussion topics of this panel it should become clear that the most appropriate method to estimate growth is not always agreed on or at least not always used during data acquisition processes. I hope that no one expects to decide today whether one can or cannot estimate growth from variable plots. Rather, we should focus on potential difficulties of estimating an item called "growth."

One may assume from the title of my presentation that I have some reservations as to whether "growth" from variable plots is a major issue or simply a historic expectation deriving from plot measurement process. Those of you who have spent a great deal of time in forest sampling or who are interested in forest sampling may regard my view with some skepticism. A few years ago, I would have agreed that growth was extremely important and must be estimated at all costs. Even today, as I am redesigning the Pacific Northwest Region inventory process, growth is a major concern. But after the past few years of data analysis and presentation for the purpose of planning and making decisions, I have come to view growth as a factor that helps explain change rather than as a single estimation.

THE REAL PROBLEM

With this in mind, I would like to emphasize the application and use of estimated growth rather than the technical aspects of the variable plot. Regardless of how a growth estimate is obtained, it must meet the needs of those intending to use it. I realize now that the real problem is defining the critical question or questions before data are compiled. I failed to do this on 11 projects I have worked on by assuming that growth was a single element of interest rather than asking what significance it had to the larger picture of change. I now believe that variable "growth" has considerable significance to researchers and model builders but only limited value to decision makers if presented as an isolated piece of data.

I would like to take a short time to further define some of my background with regard to forest sampling so you may better understand how I came to be less concerned about the single estimate of growth. I worked for the Pacific Northwest Forest and Range Experiment Station during the mid 1960's as a member of their survey crew and in the early 1970's as a member of their compilation and analysis section. Later I worked with the U. S. Department of Agriculture, Forest Service, Pacific Northwest Regional Office, further analyzing compiled data. In 1979 I became responsible for the inventory program in the Pacific Northwest Region; this position encompassed design, compilation, analysis, and projection. Because the Forest Service has been compiling data for several decades, I assumed that the type of information necessary to meet the needs of planners and the Forests had been thoroughly defined and that this aspect did not need further consideration. Therefore, my first effort was to address the sample design and data acquisition of inventory as well as complete 11 Forest projects in the necessary time frame.

THE REAL QUESTION

With the completion of these projects, it became apparent that the question being asked by all parties impacted by planning decisions (What is the volume and growth?) is not the critical question. Further discussion reveals that the real question is, "What is the volume and how has it changed?" or, with silvicultural exams, "What is the response?" These questions have been repeatedly asked within the last 24 months by Directors, Timber Staffs, Forest Supervisors, industry, industry associations, and consultants. No one stops with the question, "What is growth?" Growth is usually the term used to initiate the question, but the answer is expected to be in terms of change. These change data have been requested at the plot level, the strata level, and the Forest level so that managers can determine how volume has changed and why.

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To better answer questions regarding change, we have started redesigning the data acquisition process for our inventory. This has encompassed the evaluation of the types of volume as well as the types of growth that may occur on a plot between inventories. The issue is to identify the real change at the plot level, which should encompass the difference between d.b.h. measurements and diameter increment borings, ingrowth volume and growth on ingrowth, ongrowth volume and growth on ongrowth, and growth on mortality to simply restate items already mentioned. We have come to believe that the real need in the estimation process, regardless of the type of plot, is the ability to determine the significance of volume change over time, which is not completely answered with the estimate of growth on green trees or crop trees. It is essential that management or planning decisions reflect an awareness of change along with growth but not just growth.

We are in no way attempting to eliminate or ignore the needs of research and those involved in building projection models that are limited to growth estimates, but we do feel that both interests can be met and are necessary.

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MORTALITY ASSESSMENT: WHAT ARE THE ESSENTIALS?

Roland G. Buchman

ABSTRACT: A forest inventory, individual-tree mortality and growth models, and a computerized forest projection system are the essential elements for assessing regular mortality. The key items for each element are described and additional detail is given for the mortality model and the projection system. Discussion centers on the PROGNOSIS, STEMS, and TWIGS systems.

INTRODUCTION

Here today--but what about tomorrow? We can't sample future mortality, although we need this information for resource planning and treatment scheduling. However, the experience we've accumulated from remeasured permanent plots can be extended to the future forest. We can achieve this through projecting the current forest inventory for 5, 10, or more years using computerized mortality and growth models.

Mortality assessment using individual tree records is important because detailed tree information supports silvical decisions for planning treatments and estimating product yields as part of resource planning. In addition to retaining the tree detail present in a forest inventory, individual-tree mortality models facilitate assessment under a wide range of forest conditions.

Regular mortality--that caused by suppression, aging, pests at endemic levels, and competition for space, nutrients, and moisture--is always present; part of forest resource assessment, it can be estimated using the inventory data commonly recorded. Several regional models based on extensive information from remeasured plots are available for this use now; others are being developed.

This report presents the essential elements (the forest inventory, the individual-tree mathematical models, and the computerized system) for assessing regular mortality. Indepth discussion of mortality models and projection systems centers on two major, widely applied forest growth and yield projection systems.

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BACKGROUND

Mortality can be assessed with a one-time forest inventory. The resulting estimate is easily biased, however, because of the difficulty in determining the year of tree death or disappearance of dead trees. For these reasons, it is common inventory practice to restrict recording of dead trees to those dead 3 years or less (USDA Forest Service 1981; Bengston 1983). Recent tests show that large-scale aerial photography can identify current-year deaths, but under limited conditions (Hamilton 1980b).

To predict future mortality, we can apply the experience accumulated from remeasured permanent plots and described through mathematical models to project today's stand into the future. By restricting the projection to 1 year, we can estimate current-year mortality. Common practice is to mathematically describe permanent plot mortality information and apply these models in assessing current-year and future mortality. Hamilton (1980a) points out that the small size of most inventory plots makes them inefficient for obtaining mortality data. Buchman and Shifley (1983) identify a further limitation: many classes of trees were poorly represented on the early growth and yield plots.

Remeasured permanent plots provide critical information--the time interval of death for each dead tree and previous characteristics such as diameter and diameter growth rate for all trees. Competition can be determined by consolidating the tree information on a plot. Reliable mathematical models can be derived from frequent measurements over relatively long periods of observation.

Permanent plots were established in the early 1900's to provide data for survival tables and on growth and mortality (see, for example, Deen 1933; Krauch 1930). Repeated measurements on extensive sets of permanent plots have provided the mortality base for individual-tree mortality models for 19 species of the Lake States (Buchman 1983; Buchman and Lentz 1984), 11 species of Montana and northern Idaho (Wykoff and others 1982), and 22 species groups of the Central States (USDA Forest Service 1983). There are many sets of mortality data and models (Dudek and Ek 1980; Trimble and Shriner 1981).

Monserud (1976) and Hamilton (1980a) thoroughly discuss the data requirements for modeling mortality and the statistical methodology. Buchman and others (1983) relate the model form to survival expectations based on tree species, size, and vigor.

When used in forecasting, models are applied in another time, the future, and to the gamut of forest conditions, including size-vigor tree classes not encountered in their development. Buchman and Shifley (1983), in describing their experiences in developing and applying individual-tree mortality models for the Lake States and the Central States, point out the demands that forecasting places on these models.

ESSENTIALS

As pointed out earlier, it is possible to assess current-year mortality with just one on-the-ground inspection and, under restricted conditions, through large-scale aerial photography. However, reliable mortality estimates with these methods are possible for only very short time horizons.

Assessment of future mortality depends on the projection of a representative forest inventory. When this process is applied to a current inventory for a 1-year projection, it provides an estimate of current mortality.

Thus, assessment of future mortality requires the forest inventory data, models to project mortality based on the inventory, and a projection system. The forest inventory is basic stand information assembled to estimate forest yield by product, schedule harvests, or make silvical decisions. Included are individual tree records containing species identification, diameter, status, and quality. Also needed are some measure of plot productivity and derived stand characteristics such as basal area and average diameter. Most inventories contain many additional items; the above provide the information required for using the mortality models and for forecasting growth and yield.

Mortality models commonly depend on the species of the tree and its size and/or vigor. The mortality model in PROGNOSIS, a growth and yield projection system widely used in the Northern Region of the Forest Service, is based on tree species and d.b.h., quadratic mean stand diameter, habitat type, trees per acre, and stand basal area (Wycoff and others 1982). STEMS, a growth and yield projection system widely used in the North Central Region, requires d.b.h. and diameter growth rate in its Lake States variant (Belcher and others 1982) and d.b.h. and basal area of larger trees in its Central States variant (USDA Forest Service 1983). Competition indices, correlates of tree vigor, are commonly used in mortality models (Monserud 1976).

However, mortality models alone can't assess future mortality. They must work in conjunction with models that grow each tree and provide updated tree values to interact with the mortality model.

Finally, these models--mortality and growth--must be contained in a computerized system if they are to be applied to extensive data sets such as a forest inventory. To project the inventory, the system must be compatible with the inventory methods and data, be applicable for all timber types and stand conditions encountered in the inventory, and treat the stand as the basic unit, with projections depending upon interactions among the trees within the stand (Wycoff and others 1982).

Essentials for estimating mortality are the forest inventory, the models for mortality and growth, and the projection system. Additional description of forest inventories and growth models within projection systems can be found elsewhere (USDA Forest Service 1981; Wykoff and others 1982; Belcher 1981).

MORTALITY MODEL

Buchman and Shifley (1983) emphasize that extrapolation is involved in estimating mortality by applying remeasured permanent plot information to the forests of tomorrow and to forest conditions differing from those of the permanent plots. Mortality models must have a theoretical and empirical foundation to justify this extrapolation.

The theoretical model form (fig. 1), used for species within the Lake States, is based on biological principles and extensive tree survival data (Buchman and others 1983). This form is based on three premises:

1. The mortality probability for vigorous trees is low, but not zero. This limiting value has little relation to tree size.
2. Not all trees of low vigor will die. This probability depends on tree size; the lowest mortality occurs somewhere beyond the juvenile stage but before senescence.
3. The mortality rate decreases rapidly as tree vigor increases.

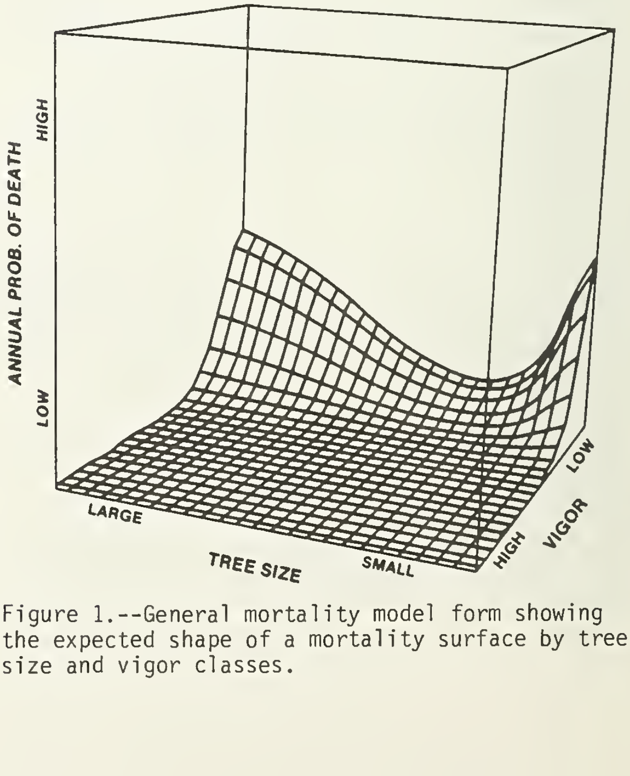

Figure 1.--General mortality model form showing the expected shape of a mortality surface by tree size and vigor classes.

These premises are consistent with the model constraints suggested by Monserud (1976) and Hamilton (1980a), but provide additional guidelines for mortality estimates for trees whose measures were not within the model's data base. In particular, these additional guidelines helped specify the probability of mortality for large, slow-growing trees and for 1- to 3-inch trees (Buchman and others 1983).

Validating the model by applying it to forest inventories independent of those used in developing the model provides the following information on extrapolation problems: (1) how the model performs on those tree size-vigor classes not present in the development data; (2) how well models developed from remeasured research plots apply to general National Forest land; or (3) how well models from fixed plot sizes apply to 10-point clusters, wherein each application involves some degree of extrapolation. Validation is important for building confidence in the model, for knowing where and when it will perform satisfactorily, and for estimating its accuracy and precision.

Finally, good mortality model performance depends on having good tree-growth information. The mortality model is usually blamed whenever poor tree survival predictions occur. However, mortality models do not operate independently from growth; we must also consider the quality of the growth information.

PROJECTION SYSTEM

PROGNOSIS and STEMS, two projection systems referred to earlier, can project the growth and mortality of a forest's trees using commonly gathered inventory data (fig. 2). They are individual-tree-based systems applicable to the wide range of forest conditions in their respective regions. These systems retain the inventory tree detail needed to support silvical decisions and product yield estimates.

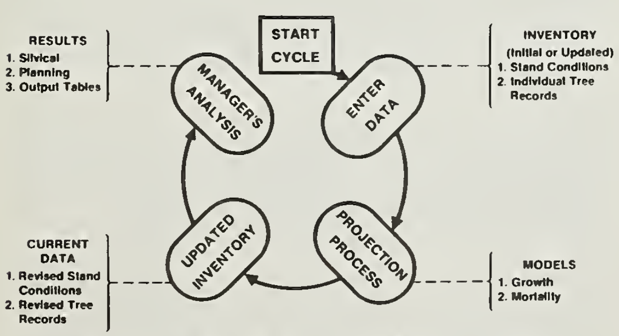

Figure 2.--One cycle of an individual-tree projection system.

Both systems readily provide the future inventory base for a mortality estimate for a survey unit, a State, or a large region. At any point in the projection schedule, they can provide the tree information that corresponds to an inventory for that moment in time.

Both systems' growth and mortality projections center on the interaction among trees within the stand. Key to this are the individual tree records that contain each tree's species and diameter. Additional ingredients include either plot size or basal area factor, or each tree's area expansion factor and stand characteristics required for estimating productivity. A detailed description of the input can be found in the user's guides (Wykoff and others 1982; Belcher 1981).

Although my discussion has centered on STEMS and PROGNOSIS, other systems are in place. For instance, the Multipurpose Forest Projection System (MFPS) has been adapted to some western forests and to forest areas in different sections of the eastern United States. The Cooperative Redwood Yield Project Timber Output Simulator (CRYPTOS) and its companion, CRYPT2, are designed for the northern coastal region of California.

Today, mortality can be assessed for individual stands by using a microcomputer. TWIGS (Belcher 1982), the North Central Station's system with Lake States and Central States variants, uses the same tree and stand input and the same growth and mortality models as STEMS. With TWIGS and a microcomputer, we can readily view the future of a stand and assess tree mortality.

WHAT NEXT?

Continuing evaluation of current mortality models and projection systems will better describe their performance and pinpoint areas requiring additional research. For example, mortality models need further evaluation with application to small trees and to large, slow-growing trees. Projection systems need evaluations under a wide range of forest conditions (Holdaway and Brand 1983). We must continue to evaluate and assemble experiences from varied applications of each system.

Planning is under way within each Forest Service Region to establish a coordinated growth and yield system. This should lead to improved and more extensive mortality models and projection systems.

Means for calibrating systems for local use will be developed. PROGNOSIS provides for self-calibration through entering previous growth information along with the forest inventory (Wykoff and others 1982). Research is under way to develop the means to modify STEMS projections on the basis of local climatic factors and soil productivity.

Additional microcomputer systems, comparable to TWIGS, will be developed to facilitate individual stand assessment.

A general procedure for assessing mortality under the more extreme tree stresses, including catastrophic conditions, is also needed but it is of lower priority than the other items. This procedure should include the means to adjust for long-term climate changes. Hamilton (1980a)

presents an approach for catastrophic mortality. Even greater benefit will accrue from a system that recognizes the varied levels and patterns of stressful conditions. PROGNOSIS extensions are available to simulate outbreaks for three insect pests (Wykoff and others 1982).

SUMMARY

A representative forest inventory, models for mortality and growth, and a projection system are the essentials for assessing current-year or future mortality. Inventory procedures that have been in use for many years provide the needed data.

Individual-tree mortality models have recently been developed that encompass the wide range of forest conditions of a region. Much work remains before all regions have the requisite models and computerized systems.

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DENSITY MANAGEMENT DIAGRAMS: A PRACTICAL APPROACH

James N. Long and James B. McCarter

ABSTRACT: Density management is the control of growing stock to achieve particular management objectives. A density management diagram was constructed for lodgepole pine in the central Rocky Mountains. To use the diagram, management objectives must first be translated into specific target levels of growing stock (stand density index). In principle, the stand is allowed to grow to the targeted upper limit of growing stock, is thinned down to the lower limit, and the process repeated as many times as necessary. In practice, modification of this simple process is usually needed. Density management diagrams are potentially valuable tools for density management planning. Although they will not replace more sophisticated computer growth and yield models, they can, together with site index curves, equations, or tables, be used by the forester to generate reasonable approximations of growth and yield for density management regimes.

INTRODUCTION

Density management is the control of growing stock to achieve particular management objectives. Although the actual control of growing stock through initial planting density or subsequent thinnings is fairly easy, deciding on appropriate levels of growing stock, given a particular management context, is much more difficult.

Various approaches to this problem have included the "seat-of-the-pants" or "30 years of experience" approach, or both; various rules-of-thumb, such as "d.b.h. times" and "d.b.h. plus" (Smith 1962); and the use of growth and yield models. All of these approaches have their advantages; they all have serious limitations.

Density management diagrams represent a practical approach to density management planning. The objectives of this paper are to briefly describe density management diagrams and to illustrate their potential with a diagram constructed for lodgepole pine (Pinus contorta) in the central Rocky Mountains.

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DENSITY MANAGEMENT DIAGRAMS

Density management diagrams are simple models of dimensional relationships presented in a graphic form. They are, in essence, simple stand average models. The diagrams, in their various forms, are based on one of several predictable size-density relationships. The most familiar of these, at least in the ecological literature, is the -3/2 self-thinning rule which relates mean tree volume to density of crowded stands. Similar, and mathematically related, size-density relationships include those relating mean height to density (Wilson 1979) and mean diameter to density (Reineke 1933).

Indexes of stand density based on size-density relationships have several characteristics which make them excellent tools in density management. For example, they are, for crowded stands, highly predictable. They are independent of site quality and stand age. And perhaps most importantly, they are excellent predictors of levels of competitive interaction, for example, growth-growing stock relations and degree of site occupancy (Long and Smith 1984).

The simplest density management diagrams are basic two-parameter models. For example, Reineke (1933) constructed a nomogram (fig. 1) relating quadratic mean diameter (Dq) in inches, trees per acre (TPA), and stand density index (SDI). Wilson (1979) devised a similar diagram equating mean height, density, and index of stand density based on spacing as a percentage of height. The most familiar density diagrams are of the type developed by Gingrich (1967). These diagrams relate Dq, stand basal area, density, and levels of growing stock (fig. 2). Commonly in the Gingrich-type diagrams the levels-of-growing-stock lines are based on crown competition factor (CCF) (Krajicek and others 1961).

To use such a diagram, management objectives must first be translated into specific target levels of growing stock. In principle, the stand is allowed to grow to the targeted upper limit of growing stock, is thinned down to the lower limit, and the process repeated as many times as necessary (fig. 3). In practice, modification of this simple process is usually needed to accommodate some aspect of the management objectives such as minimum merchantable tree size or minimum volume removal per entry. Appropriate upper and lower limits will, of course, vary with both species and management objectives.

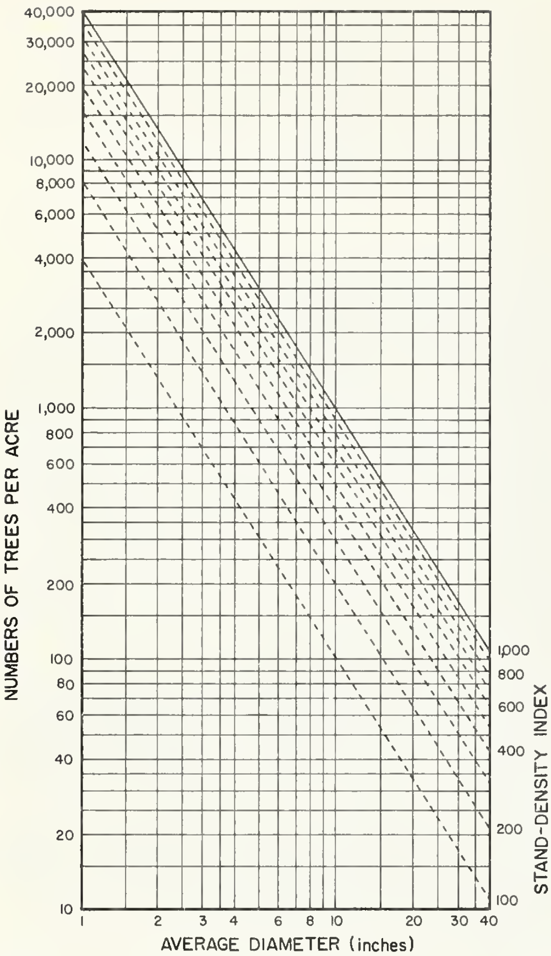

Figure 1.--Nomogram relating Dq, TPA, and SDI (Reineke 1933).

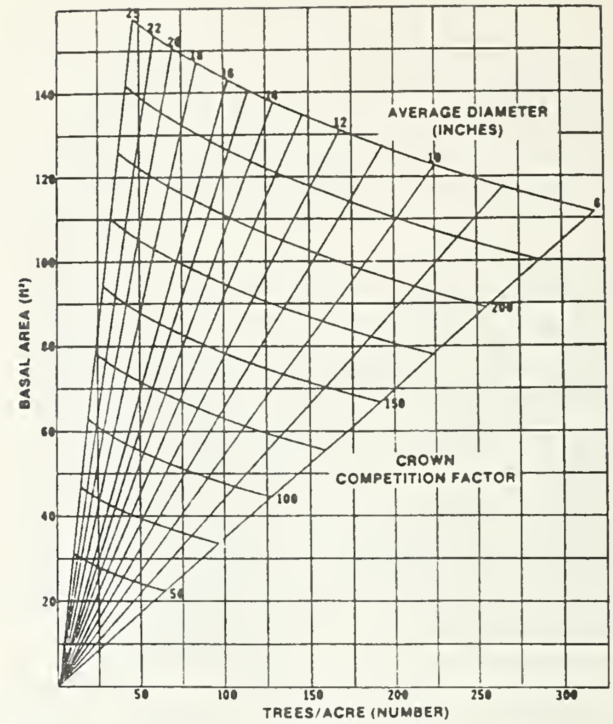

Figure 2.--Stocking guide for black walnut (Schlesinger and Funk 1977).

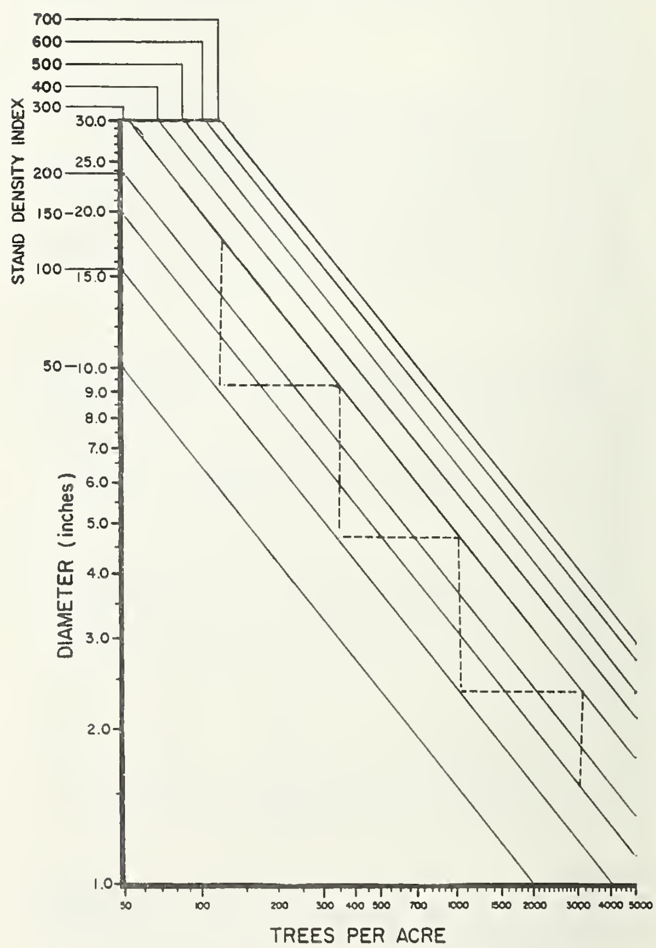

Figure 3.--Hypothetical density management regime using SDI to set upper and lower limits of growing stock.

For a given species, dimensional relations are fairly predictable. Therefore it is possible, with the inclusion of additional size parameters, to greatly improve the utility of a diagram with but a slight increase in its complexity. Figure 4 is a density management diagram constructed for lodgepole pine, in the central Rocky Mountains (McCarter 1984). This diagram has Dq and TPA on the two major axes; both are plotted on a logarithmic scale. The parallel diagonal lines represent SDI. The uppermost line corresponds to an SDI of 700, approximating the maximum combination of Dq and TPA possible stands of this species. The two additional sets of lines represent mean height of site trees (Hs) and total volume. Similar density management diagrams have been developed for many of the commercial timber species of Japan (Ando 1968), coast Douglas-fir (*Pseudotsuga menziesii*) (Drew and Flewelling 1979), loblolly pine (*Pinus taeda*) (Flewelling 1981), as well as lodgepole pine (Flewelling and Drew in press).

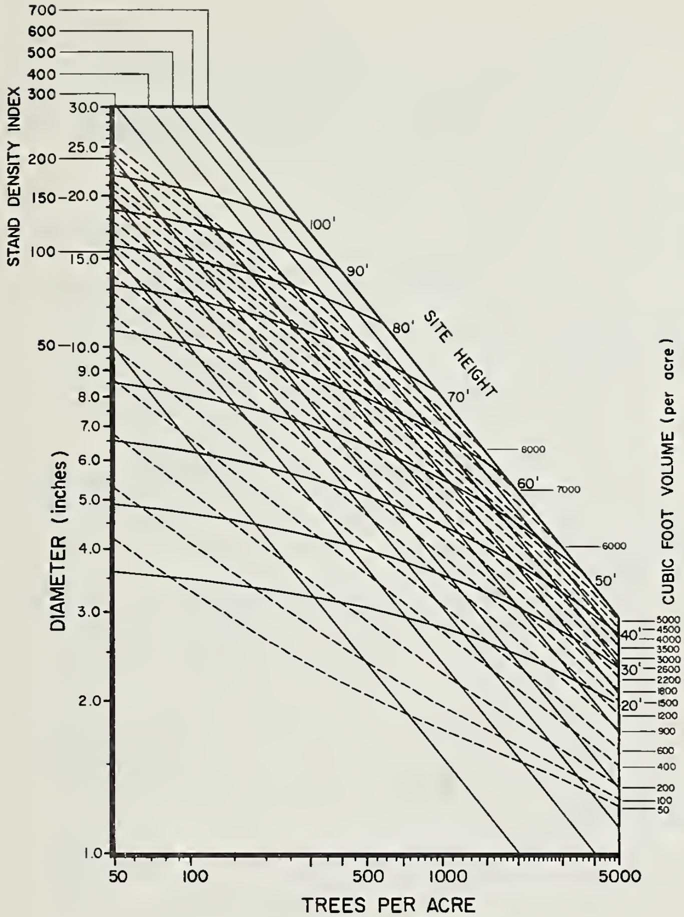

Figure 4.--Density management diagram for lodgepole pine. (An 8½- by 11-inch copy of the diagram is available, on request, from the authors.)

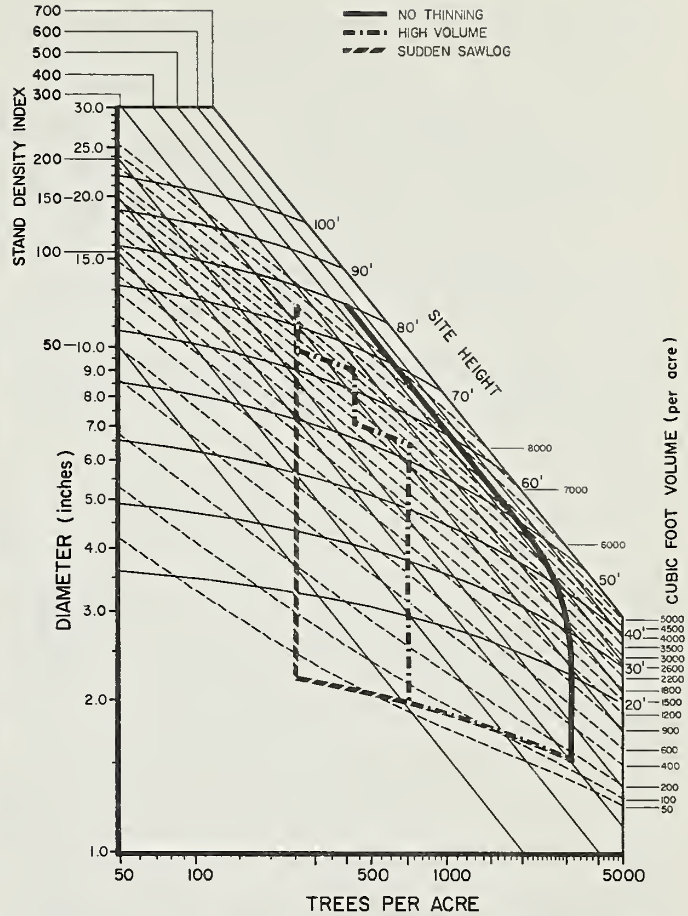

Figure 5.--Alternative density management regimes.

USE OF THE DENSITY MANAGEMENT DIAGRAM

Potential uses of the density management diagram will be illustrated by example. Figure 5 illustrates three alternative density management regimes for a hypothetical lodgepole pine stand with 3,050 TPA and Dq equal to 1.5 inches. Site index (base age 100) is assumed to be 80. It is also assumed that commercial thinning requires a Dq of at least 6 inches and a volume removal of at least 1,000 ft^3/acre/entry. Under each of the alternative regimes, an end-of-rotation Dq of 12 inches is assumed.

In the first, or no thinning, alternative, Dq and Hs increase with little, if any, reduction in TPA until the stand begins to self-thin (SDI > 400). Subsequent increases in average size are accompanied by declining TPA so that SDI remains more or less constant at a level somewhat below the species maximum (Drew and Flewelling 1977).

Because mortality which may occur before onset of self-thinning is exceedingly difficult to predict and is largely independent of density (Drew and Flewelling 1979), in most cases it should be ignored in the planning of density management regimes.

Time can be included in this development by the use of site index curves or tables and the estimates of Hs from the diagram. For the no thinning alternative, when Dq equals 12 inches, the estimate of Hs is 80 ft. Lodgepole pine variable density site index tables for SI_{100} = 80 ft (Alexander and others 1967) indicate a rotation age of about 132 years (table 1). The increase in age beyond that suggested by the site index (that is, 132 years versus 100 years when Hs = 80 ft) reflects the negative interaction between height growth and density incorporated into the Alexander and others (1967) tables.

In using the diagram to plan a density management regime it is necessary to first translate the management objectives into appropriate levels of growing stock, that is, upper and lower limits to SDI. For example, the second, or high volume, alternative is designed to maintain levels of growing stock sufficient to insure full site occupancy (SDI > 250) but avoid self-thinning (SDI < 400). In this regime we actually use SDI = 350 as the upper limit to growing stock. This somewhat low value, as opposed to 400, illustrates the idea that minimum levels of individual tree vigor may often be a factor in density management planning. Berryman (1982) suggests, for example, that reducing competition and thus increasing tree vigor may represent the best silvicultural insurance against catastrophic losses to the mountain pine beetle.

Table 1.--Comparison of three density management alternatives[1]

	Age	Hs	TPA		Dq		Volume removed
			Before	After	Before	After	
	Years	Feet			Inches		Ft^3/acre
			No-thinning				
Final harvest	132	80	410		12.0		8,500
Total yield							8,500
MAI							64 ft^3/acre/yr
			High volume				
PCT	5	8	3,050	700	1.5	2.0	
CT1	65	54	700	440	6.4	7.2	1,000
CT2	83	65	440	250	8.8	9.6	1,000
Final harvest	104	76	250	0	12.0	0	6,000
Total yield							
MAI							8,000
							77 ft^3/acre/yr
			Sudden sawlog				
PCT	5	8	3,050	250	1.5	2.2	
Final harvest	95	76	250	0	12.0	0	6,000
Total yield							6,000
MAI							63 ft^3/acre/yr

[1] Mean annual increment based on age at final harvest; includes yield from commercial thinnings and final harvest only.

The target end-of-rotation Dq (12 in) and growing stock upper limit (SDI = 350) define a stand with approximately 250 TPA and 6,000 ft^3/acre. It is then easy to work backward through the rotation as indicated on the diagram (fig. 5). A precommercial thinning is required to set up the first commercial thinning. With two commercial thinnings and the final harvest, this regime yields an estimated 8,000 ft^3/acre and mean annual increment (MAI) of about 77 ft^3/acre/yr.

The third, or sudden sawlog, alternative uses the same growing stock upper limit (SDI = 350) but eliminates the commercial thinnings. A heavy precommercial thinning is used to set up the final harvest. This regime emphasizes the production of final crop trees in a relatively short rotation (95 years) at the expense of some potential yield (table 1). Compared with the high volume alternative, this regime reduces total yield by 33 percent, but because of the shorter rotation reduces MAI by only 18 percent.

The graphical representation of dimensional relationships by density management diagrams can provide a great deal of insight into the way that even-aged stands develop. For example, the tradeoff between either rapid individual tree growth and short rotations or greater yields associated with higher levels of growing stock is easily illustrated with the diagram. The consequences to growth and yield of various management objectives and constraints can be interpreted using the diagram. If, for example, the minimum Dq assumed to be required for a commercial thinning entry was reduced, the total yield and MAI of our high volume regime could be substantially increased.

Density management diagrams represent potentially valuable tools for density management planning. Their incorporation of size-density based indexes of growing stock (for example, SDI) provide the user with a mechanism with which to quantify those aspects of stand and individual tree performance important in the context of specific

management objectives. Although density management diagrams will not replace more sophisticated growth and yield models, they can, together with site index curves, equations, or tables, be used to generate reasonable first approximations of growth and yield for density management regimes.

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CALIBRATION CONSIDERATIONS IN USING MAJOR MODELING SYSTEMS

Ralph R. Johnson and Gary E. Dixon

ABSTRACT: The Stand Prognosis Model has been recalibrated for areas in the northern Rockies, central Rockies, and Pacific Northwest. In addition to the mechanics of refitting growth and mortality functions, other items have surfaced that add to the complexity of moving a major model to a new area. Field visits by modeling personnel are mandatory. Aggregating data from a variety of sources, understanding what data you have, how it was collected, and its integrity is time consuming. Growth and mortality models need to reflect the kind of data available and local biology. Recalibration needs to be linked with training new users. As new models are brought into a production mode, computer code upgrades and documentation become more complex, as is the interface of users with the new model.

INTRODUCTION

Over the past 6 years, the Stand Prognosis Model (Stage 1973) has been recalibrated for a number of forest conditions in the Western United States (fig. 1).

Figure 1.--Location of geographic variants of prognosis in the Western U. S.

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In the process of recalibration, many lessons have been learned about moving major models to new areas. Examples given in this paper illustrate these lessons. Not all of them are mensurational. Mathematical models must be embedded in computer code, and users must be trained to use the completed program. Once the system is built, maintenance, support, and enhancement are required. This paper covers the broader subject of moving, maintaining, and supporting the complete model, not just the mensurational aspects.

BUILDING THE SYSTEM

Developing Local Knowledge

Often the mensurationist is given data sets for an area and asked to produce functional relationships from them. If the mensurationist is not familiar with that area, it is easy to miss a key variable or not know when something is out of whack.

One of the first steps in the recalibration process is a field visit, which may yield local sources of data that are unknown to the central office. Discussions with field personnel provide insights about data integrity and history that affect the modeling process and are not included in any written documentation. When a user's data and ideas are considered in the modeling process, user confidence in the model is enhanced. In our present project in south-central Oregon and northeastern California, such a trip surfaced enough information to require an additional 2 months of data acquisition and aggregation. This resulted in a large amount of managed stand data that bolstered user confidence and enhanced the model.

The field visit opens communications with the user community. Users become familiar with those who did the work and feel more free to critique and use the final product. It's easier to talk on the phone to someone when you can visualize their face, and future contacts will most likely be by phone or letter. Field personnel are invaluable in the critique phase of model development.

During the field trip, open discussion can take place about handling unique conditions and the various types of information needed to run the model. Some examples of unique conditions requiring special consideration are hardwoods in the Klamath Mountains, pumice soils in eastern Oregon, and mountain pine beetle in the Tetons.

Aggregating Data to a Common Computer

Curtis' (1983) detailed discussion of items needed for growth and yield research on permanent plots is invaluable for anyone using data from a variety of sources. The appendix of Curtis' paper lists key variables that are important in recalibrating PROGNOSIS models. Variables as minor as month of survey are critical if growth is recorded by remeasurement. Frequently, an apparently good data set is missing a significant variable, but this is difficult to determine without a complete list of variables. In the case of PROGNOSIS recalibration, some measure of tree vigor (for example, crown ratio) has typically been missing.

The sample design must be known for each data set. Was the sample taken with fixed area plots, variable radius plots, or a combination of plot types? We require a plot installation and code interpretation manual with each data set we receive. Frequently, careful reading of the inventory instructions and codes manuals reveals that some trees were not recorded. For example, rough cull and cull saplings may not be recorded in some inventories. In these cases, growth records may be biased toward "best" trees.

Problems usually arose with the measurement of mortality. Were trees killed by insects or disease? Were trees recently removed by logging or dead before removal? In forest inventory, mortality is often coded as recent (last 5 years) or older dead (more than 5 years). We have serious concern about the ability of cruisers to estimate the age of mortality that accurately.

Different units of measure for the same variables must be reconciled before data can be aggregated. As we have moved PROGNOSIS to new geographic areas, we have encountered a variety of measures of productivity. Some areas use habitat types, some use site index, and still others use soil types. Site index differences are another good example. In the same geographic area, different administrative units use different site index curves for the same species.

Accessing data sets that are not the most current edited version is another problem. A given administrative unit's computer file may resemble another's on the outside. On the inside, however, they may be different, and using the old file can be a costly mistake.

Calculating the Stand Variables

In building PROGNOSIS models, individual tree records are the basic record; however, stand attributes need to be attached to them. Basal area per acre, crown competition factor, top height, trees per acre, and the tree's social position are calculated. Stand values are calculated for the beginning and end of the growth period. The importance of knowing the data and getting it standardized cannot be overstated. Getting the wrong basal area factor or wrong mortality estimation procedure will lead to an incorrect result.

The PROGNOSIS model has until recently been built using 10-year growth periods for big trees. If the inventory remeasurement period for a particular data set was 8 years, it must be adjusted to a 10-year measure so it will be compatible with the other data sets. Although increment cores are usually read for the last 10-year growth interval, we have encountered plots with increment recorded in rings per inch. These kinds of anomalies are uncovered by reading the manuals and talking to owners of the data.

Data Editing

Once the data are in a common computer file, scattergrams and descriptive statistics are used to look for errors. Data listings should also be examined to look for summarization program problems. As an example, in our analysis, a point crown competition factor (CCF) variable was printed and written to a mass storage file; however, only a subset of the data was printed and used in error checking. When the whole data set was examined, the point CCF variable was constant for records after the print was stopped. The problem, an errant GO TO statement, was quickly located and corrected.

Getting good clean data from which to build a model is a time-consuming and demanding job. In our experience, this has typically taken about 4 months, unless all of the available data are from one source. Even with one source, the data usually have been collected over a number of years, during which coding conventions have changed.

Fitting Models

For the geographic variants we have developed, growth and mortality submodels were refit while the basic operating system was essentially unchanged. We wanted a model that reflected local forest conditions but that was still a PROGNOSIS model. Of the parts we have refit, some items are worthy of note.

Volume equations should be local. They should be the same ones used in stand examination programs and cruising programs. Incompatible equations result in frequent phone calls from users asking why the answers are different. Having separate equations for merchantable products and total cubic volume leads to the same inconsistency. A taper equation with a mathematically compatible cubic equation is preferred. Board foot volumes can also be derived from the taper equations. In addition, the equations must account for a wide array of merchantability standards since a model built today will be used tomorrow, and merchantability standards are constantly changing. We tried using form class equations, but the results were unacceptable. It was difficult, if

not impossible, to allow for change in form class over time and with changing tree conditions.

Height growth measurements are plagued with measurement errors and lacking in most data sets. Felled tree studies are the best solution to this problem. Although these studies are expensive, a variety of growing conditions can be sampled for and, if stem measurements are made at the time of felling, the trees can be used for volume table construction.

In the present variants of PROGNOSIS, height growth is treated differently for large and small trees. Small tree projections are made using a 5-year model; large tree height projections use a 10-year model. Five-year height growth measurements for small trees have been collected for several years in the stand exam process in the Northern Region. Unless trees are in plantations (rapid growing), measuring height growth without destructive sampling is difficult for trees over 2 inches d.b.h. For species like western redcedar (Thuja plicata) and hemlock (Tsuga heterophylla), destructive sampling is even necessary for trees less than 2 inches d.b.h.

Height growth is further complicated by defoliation caused by pests such as western spruce budworm. When defoliation has occurred, it should be indicated on the data set. Forest Pest Management has overlaid budworm defoliation maps on stand maps to determine what stands are likely to be influenced by the budworm.

Large tree height growth models have taken two basic forms. Wykoff and others (1982) present log linear models used in the Inland Empire variant of PROGNOSIS. When height growth data are available, the log linear form is used. Lacking height growth data, a technique using the Johnson (no relation to this author) SBB distribution is used (Schreuder and Hafley 1977). Figure 2 illustrates the form of this distribution. Figure 3 illustrates the data set used to fit the distribution. We fit the SBB distribution to trees of selected attribute classes such as crown ratio, site index, habitat type, and basal area in larger trees. Diameter growth drives this model, and a tree is assumed to maintain the same relative position in the distribution from the beginning to the end of the projection period.

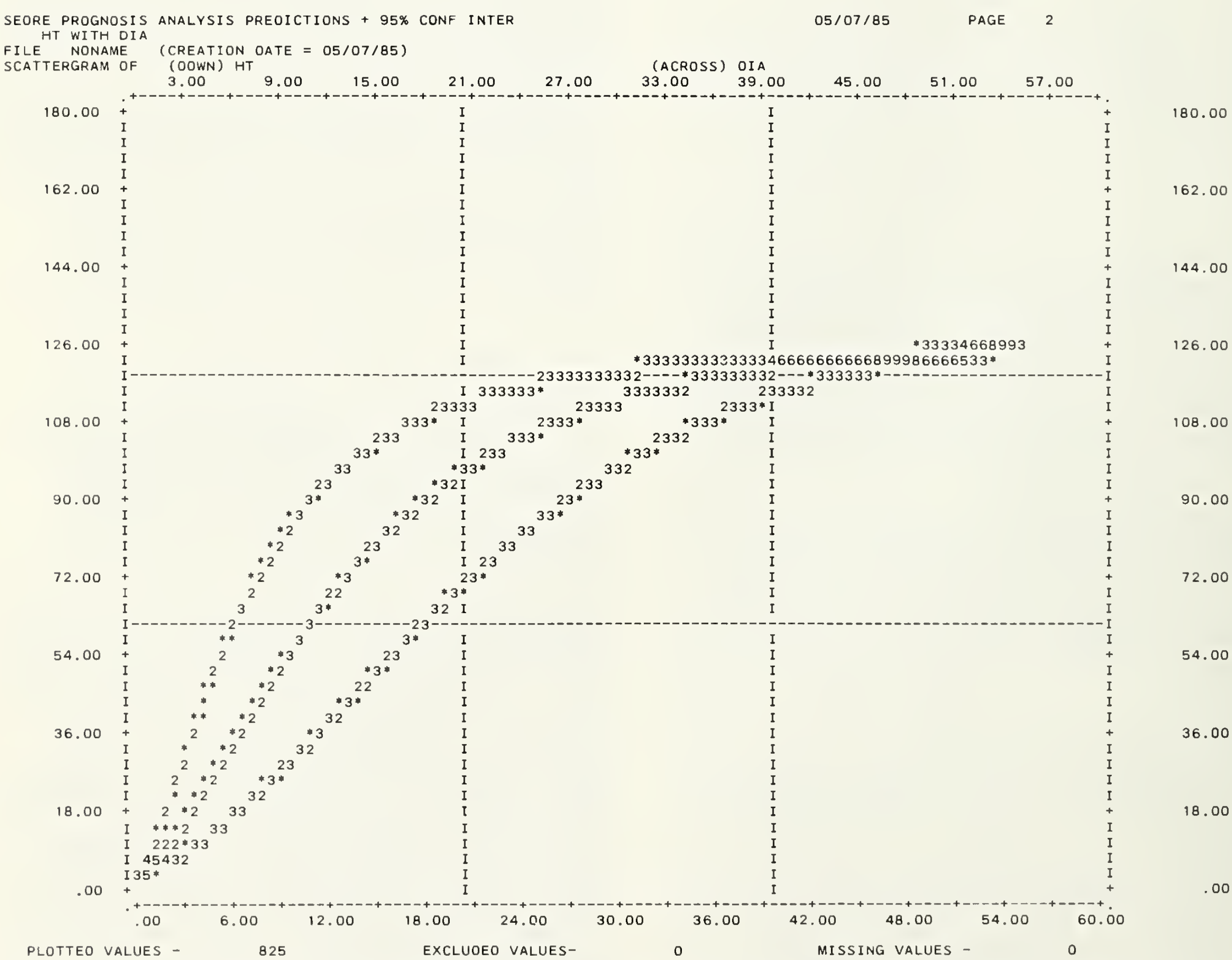

Figure 2.--Plot of median, upper 95 percent confidence band, and lower 95 percent of Johnson's S_{BB} distribution for ponderosa pine (Pinus ponderosa).

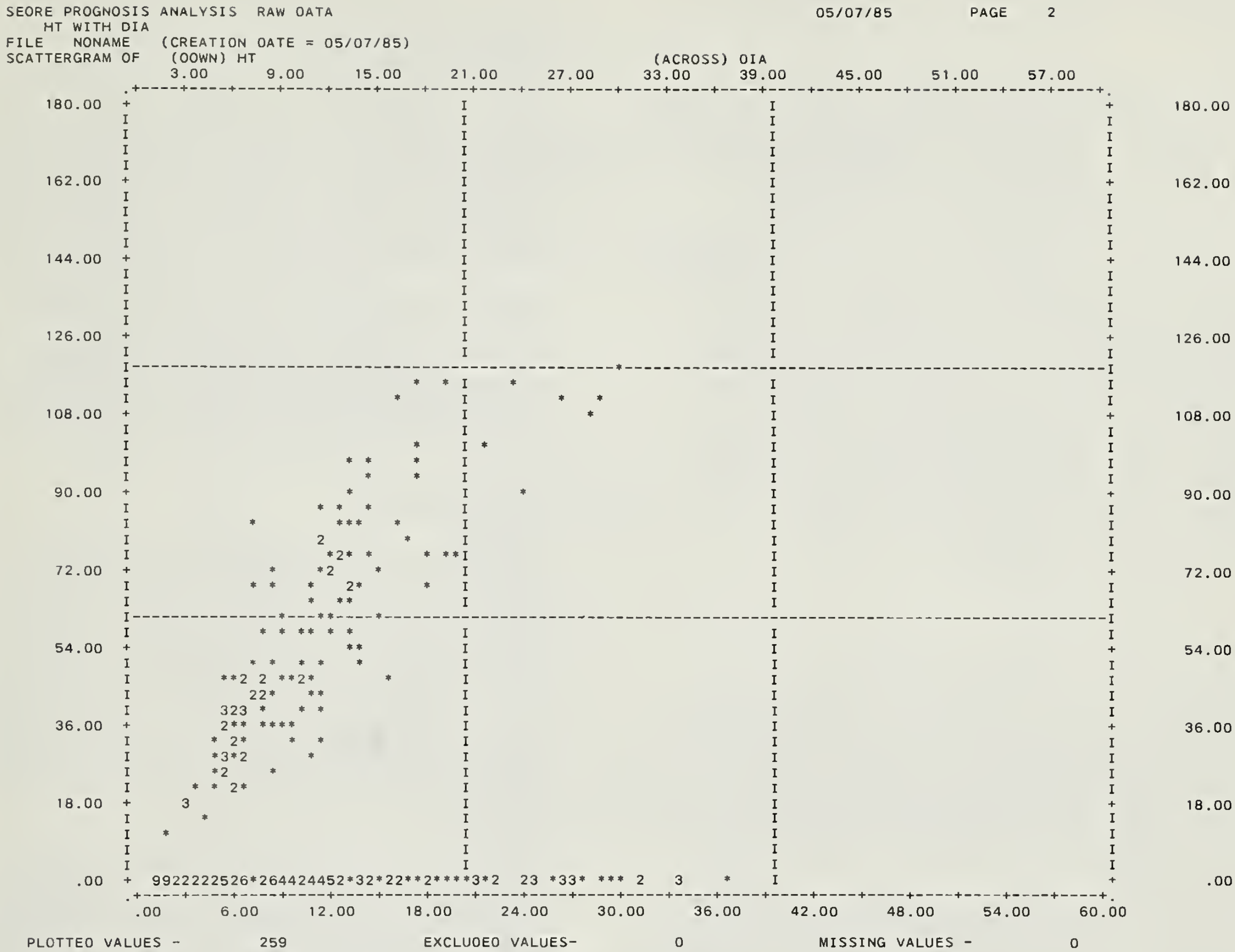

Figure 3.--Scattergram of heights with diameters for data used in fitting the S_{BB} distribution plotted in figure 2.

Diameter growth models have taken two forms. Wykoff's log linear forms are used for conifers and a nonlinear form is used for hardwoods. In the Utah variant of PROGNOSIS, we used an adaptation of Wykoff's forms suggested by Stiff and others (1982) for conifers. This adaptation uses point density as well as, or in place of, stand density. For aspen (Populus tremuloides), we used nonlinear equations of the type used in the STEMS Lake States Models (Holdaway 1984). Placement of STEMS-type equations into the PROGNOSIS superstructure was accomplished with few computer code modifications.

Fitting diameter growth models is greatly enhanced by a well-thought-out and debugged analysis package. Such a package, developed by Wykoff, is being used in our refitting of PROGNOSIS. These routines use a combination of custom and commercial software. REX (Grosenbaugh 1967) and SPSS comprise the core of the package. Even the use of Wykoff's analysis package requires recoding to accommodate variables unique to the data being analyzed.

Mortality functions have taken a variety of forms. The new techniques of Hamilton (1984) or Buchman (1979) require a growth measure not available in our data sets, so we could not fit such equations. In the Utah variant, mortality rates were based on inventory estimates of 5-year mortality. Diameter was used as reported in Wykoff and others (1982), in addition to a social position and density variable. The normal stocking density equation was refit to inventory records in the Utah, Teton, and south-central Oregon/northeastern California geographic variants. In eastern Montana, we used techniques described in Wykoff and others for mortality estimation; however, the estimates were adjusted using results of large-scale aerial photography (Hamilton 1984).

National Forests in the Inland Northwest are installing permanent plots which will be used in providing data for developing future mortality models and testing existing models. Through permanent plots, actual mortality and growth can be monitored.

MAINTENANCE AND SUPPORT FOR A MAJOR MODELING SYSTEM

Once a model is built, whether it is entirely new or a recalibration of an existing model, it must be maintained and supported to be accepted for widespread, long-term use. Potential users must be trained to use the model and frequently require assistance in error tracking when problems arise. Model errors must be corrected as they are discovered, and model adjustments may be necessary as the model is applied to a wide variety of situations. Additional features may be requested, and links to auxiliary routines might be necessary. If maintenance and support are lacking, users may become discouraged and stop using the model or attempt to maintain it themselves. User maintenance quickly leads to many slightly different versions of the same model, all of which are inconsistent with each other, and none of which have all the errors and inconsistencies removed or the latest enhancements incorporated.

Model Implementation

When a model is ready for implementation, it should go through a prerelease testing phase consisting of two or more steps. These steps may be lengthy and rigorous and, in some cases, several iterations may be required. The purpose of this phase is to make sure the model is behaving properly mathematically, biologically, and intuitively, given a limited range of input specifications.

The first step is to make sure the model is functionally correct. Typically, only the model developers are involved at this point. The model is run on a test data set and the output examined. General relationships are checked first. Examples would be tree (or stand) height increasing as diameter increases or the number of trees in the stand decreasing over time. Relational magnitudes are checked next. For example, a tree (or stand) with a 1-inch diameter growth and 100-foot height growth over a 10-year period would be suspect. Relational sensitivity is checked by changing model control variables and comparing outputs for a given test data set. This whole process may be repeated for several test data sets until the model developers are satisfied with model behavior and confident in the mathematical relationships.

The second step is a limited application test. This step involves the model developers and a few selected users. These users run the model on their own data sets and provide feedback to the developers about model behavior, functional relationships, improvements, refinements, and general applicability and use. Modeling errors are commonly discovered at this point, and many valuable suggestions for model improvements surface.

Once a model is ready to be released for general use, training sessions are held. Training is done at two levels. Managers are given a general training course lasting 1 to 2 days. Course content includes a model overview; gross relationships; types of output expected; strengths, weaknesses, and limitations of the model; and the range of model applicability. Potential users should be given a week of technical training. This course covers specific relationships, model theory, model control variables, output interpretation, and strengths, weaknesses, and limitations of the model, along with a hands-on session to run the model.

Another form of training takes place after a model becomes established. Special seminars covering a specific application of the model can be given in connection with other meetings. This broadens the model's area of use and introduces the model to additional potential users.

Model Maintenance

Maintenance of a modeling system involves changing the computer code in response to some need or correction, keeping users informed of these changes, linking the model to auxiliary routines, and, in some cases, maintaining auxiliary routines. The importance of this job and the amount of time and resources required to do it correctly are frequently underestimated. Individual changes may take from a few minutes to several weeks, and all changes need to be fully documented.

Most changes are requested by the model users. Typically, these are changes in the output tables to print out additional information or parameters or requests for additional features and links to auxiliary routines. Model errors are usually discovered by users, who occasionally request changes in the way values are calculated.

Changes can also be requested by the model developers. These changes are usually technical changes such as correcting errors, implementing new methodology in the mathematical relationships, or upgrading the model to a more efficient or expanded level.

Regardless of who sponsors the change, managers and users must be kept informed of the model's status. For managers, the length of time between implementing the change and informing them of the change is usually not critical. In these cases, a formal letter documentation is the best.

Users, on the other hand, should be informed as soon as possible of a change. For them, some sort of bulletin system that prints every time the model is used is best. The information is thus available immediately, and every user is informed. Figure 4 is an example of the bulletin system used for PROGNOSIS.

Linking the model to auxiliary routines is often an overlooked part of model maintenance. Auxiliary routines fall into two categories, preprocessors and postprocessors. Preprocessors range from data manipulation routines which put input data into the proper format to interactive

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@XQT TMYIELD*PROGNOSISSCU.PMOD
                                ****************************************************************
                                *                                                              *
                                ********  BULLETIN CONCERNING THIS VARIANT OF PROGNOSIS  ********
                                *                                                              *
                                ****************************************************************

********** ON APRIL 5, 1985 THE SUBMITTAL SYSTEM OPTIONS OF STANDTAB AND SCATTER
        WERE CORRECTED.  THEY SHOULD BOTH WORK CORRECTLY FOR LEVEL 4.0 AND 5.0 VARIANTS
         THE SUBMITTAL SYSTEM KEYWORD  SCATTER  WILL NOW PRODUCE BOTH SCATTERGRAMS AND DIAMETER
        FREQUENCY TABLES FOR THE CYCLES REQUESTED

********** ON MARCH 19, 1985 THE TREELIST KEYWORD FORMAT WAS CHANGED.
        THE NEW FORMAT IS AS FOLLOWS:
        FIELD 1-- DATE/CYCLE NUMBER
        FIELD 2-- DATE/CYCLE NUMBER
        FIELD 3-- DATE/CYCLE NUMBER
        FIELD 4-- DATE/CYCLE NUMBER
        FIELD 5-- DATE/CYCLE NUMBER
        FIELD 6-- DATA SET REFERENCE NUMBER
        FIELD 7-- HEADING SUPPRESSION CODE

****** ON APRIL 30, 1985 SUBROUTINE MORTS WAS CHANGEDTO REFLECT NEW MAXIMUM SDI VALUES OF
         SPECIES     MAX SDI  .85 LEVEL   REFERENCE
         SRF           1207      1027       SCHUMACHER 1928
         WF            1004       854       SCHUMACHER 1926
         SP,IC,ES       881       749       DUNNING & REINEKE
         WP             763       649       HAIG 1932
         MH             758       644
         DF             737       627       SCHUMACHER 1930
         PP             685       583       MEYERS 1938
         J              616       524
         LP             413       352       DAHMS 1964

ON APRIL 30, 1985 SUBROUTINE MORTS WAS CHANGED YOU MAY
        NOTICE A DECREASE IN MORTALITY RATES IN EARLY-MID PROJECTION YEARS


        IF YOU WANT FURTHER INFORMATION ABOUT THESE CHANGES, OR IF THESE CHANGES CAUSE YOUR RUN TO ERROR  --
        PLEASE CONTACT GARY DIXON (WOTM, FT. COLLINS) AT FTS 323-1814 OR COMMERCIAL (303) 224-1814.  THANK YOU.
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Figure 4.--Sample computer information bulletin for PROGNOSIS system used on the Fort Collins computer.

programs that build runstream files necessary to run the model. Postprocessors range from routines which further analyze model output to ones which store model outputs on permanent files. These auxiliary routines must also be maintained and upgraded to accommodate changes to the model.

User Support

For large systems, user support is as important as model maintenance. There are three basic interrelated categories of user support: (1) providing assistance in using the model and auxiliary routines, (2) providing assistance in error tracking and problem solving, and (3) answering users' questions concerning model applications.

Providing assistance in using the model and auxiliary routines is the "how to" category. This includes training sessions covering model usage, helping users with computer control language commands, answering questions concerning data preparation and model control commands, interpreting output, and debugging runstreams.

The second category is the "help!" category. When errors are discovered or problems arise when running the model, they must be traced through the program to find the cause. Then the errors must be corrected, and the users should be notified. Often problems are caused by users' mistakes or by extending the model relationships beyond their intended bounds. Adequate training can help minimize these difficulties.

The third category is the "what if" category. It includes questions such as: What happens if the model is used outside its intended geographic range? What happens to the model relationships if the user is missing a variable on the input data? Which variant can I use for the Bitterroot National Forest? And a host of other questions.

Documentation

Proper documentation is an important part of maintaining any system, especially if a model has several geographic variants. It is often difficult to remember what change was made, when it was made, and to what variants it applied. Proper documentation is necessary to answer technical questions, resolve challenges to procedures that were used, and allow other programmers to follow what was done.

Several forms of documentation are important. Comment statements in the computer code are useful to programmers and some users and represent a minimum level of documentation. A central file outlining code changes should also be maintained. For programmers and nonprogrammers, this provides a quick and easy way to resolve questions. Backup copies of the model should also be maintained for future

reference and use. Sometimes an old version of a model must be used to reproduce a given output, analyze an alternate management strategy consistent with already established results, or to respond to legal inquires. Also, files containing the model may be damaged or lost from the computer system. Without proper documentation, resolving these problems would be almost impossible.

Planning for System Review and Evaluation

Sometimes when a model is developed or extended into a new geographic range, some relationships are weak because of a lack of data. Other times, after a period of use it becomes apparent that the model just is not operating the way it should or that some enhancements would make it more useful. These cases point out the need for a careful system review and model evaluation once a model is in use. These reviews can help direct new research to strengthen weak relationships or correct errors and inconsistencies. Naturally, some system review and evaluation comes just from feedback as the model is used; however, planning for a formal review and evaluation can improve most models.

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RMYLD UPDATE: NEW GROWTH AND YIELD RELATIONSHIPS FOR ASPEN

Carleton B. Edminster and H. Todd Mowrer

ABSTRACT: Whole stand growth and yield relationships have been developed for even-aged stands of aspen in the central Rocky Mountains and incorporated into a new species-specific subroutine of the RMYLD model. Potential production is estimated for various combinations of site quality, rotation age, and initial thinning intensities. Merchantable cubic-foot volume is maximized at relatively high stand densities. Early precommercial thinning produces fewer but larger trees at rotation with relatively small decreases in total yield compared to unthinned stands.

INTRODUCTION

There are 3.78 million acres of commercial aspen (Populus tremuloides) forest in Colorado, Utah, and Wyoming (Green and Van Hooser 1983). More than 75 percent is in Colorado. The net bole volume of aspen growing stock in these three States was more than 3.25 billion cubic feet in 1977.

The potential of aspen for wood production and management has been relatively neglected. In recent years the wide distribution of aspen, concerns for timber supplies and stand conditions, and improved utilization have increased interest in its growth and yield characteristics and management potential (USDA Forest Service 1976). Baker (1925) studied the growth and yield of aspen in central Utah and felt his results would be generally applicable throughout the central Rocky Mountains; however, his yield tables are limited to narrow ranges of stand density and geographic distribution of growth plots. Although estimates of future growth and yield of aspen have been made by reference to these early tables or by reference to stock tables of similar stands, both methods have serious limitations. The early yield tables are not representative of a wide variety of stand densities, and the use of stock tables is limited by the accuracy of expectations about future conditions of the subject stand.

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MODEL DEVELOPMENT

Silvical characteristics of aspen make it an ideal species for a whole stand, even-aged growth and yield model such as RMYLD (Edminster 1978). In 1979 in cooperation with Colorado State University, a study was begun to collect growth data and develop whole stand growth and yield relationships for aspen stands in Colorado, southern Wyoming, and northeastern Utah. Data were collected from 101 temporary plots located in single, even-aged clones. The clones were purposively selected to represent a wide variety of stand conditions (table 1).

Table 1.--Summary of stand conditions sampled in the aspen growth study

Characteristic	Mean	Minimum	Maximum
Site index (feet)	63.3	29.0	111.0
Average age at b.h. (years)	68.6	17.0	131.0
Trees per acre	1,088.0	128.0	5,469.0
Basal area per acre (ft^2)	160.5	12.0	351.0
Average diameter (inches)[1]	6.6	1.6	15.0
Average dominant and codominant height (feet)	48.6	14.8	100.7
Total volume per acre (ft^3)	3,551.4	97.2	12,879.2
Merchantable volume per acre (ft^2)[2]	4,498.0	187.2	12,311.6
Sawtimber volume per acre (board feet)[3]	22,724.1	2,238.0	61,031.0

[1]Average diameter is the diameter of the tree of average basal area.

[2]Values for merchantable volume based on 57 plots with average diameter 5.0 inches and larger. Merchantable volume computed for trees 5.0 inches d.b.h. and larger to a 4-inch top.

[3]Values for sawtimber volume based on 36 plots with average diameter 7.0 inches and larger. Sawtimber volume computed for trees 7.0 inches d.b.h. and larger to a 6-inch top.

Relationships to project average stand diameter, average dominant and codominant height, and periodic stand basal area growth were developed,

as were relationships to estimate changes in average tree characteristics and numbers of trees per acre due to thinning from below to various levels (Edminster and Mowrer in preparation). Stand volume equations are used to compute total and merchantable cubic-foot and board-foot volumes per acre. These relationships were incorporated into a new species-specific subroutine for RMYLD. Growth and yield estimates contained in this paper are based on these relationships.

STAND CONDITIONS SIMULATED

Yield simulations were made for the following range of initial stand conditions and management controls:

1. Site indexes at 80 years of age at breast height (b.h.) are 40, 50, 60, 70, 80, and 90 ft. (Edminster and others 1985).
2. Average b.h. is 20 years.
3. Average stand diameter (d.b.h.) is related to site index as follows (average stand diameter is the diameter of the tree of average basal area):

Site index (ft)	Initial d.b.h. (in)
40	2.0
50	2.2
60	2.4
70	2.6
80	2.8
90	3.0

4. Stand density is 2,000 trees per acre.
5. No catastrophic mortality occurs during the rotation.
6. Single precommercial thinnings are made at b.h. age 20 to growing stock levels 80, 100, 120, 140, 160, and 180. (Growing stock level [GSL] is defined as the residual square feet of basal area when average stand diameter is 10 inches or more. Basal area retained in a stand with an average diameter of less than 10 inches is less than the designated level [Edminster 1978]). Stands are also left unthinned for the rotation.
7. Maximum rotation age at b.h. is 120 years, with a clearcut regeneration method.
8. Minimum size for inclusion in merchantable cubic volume is 5.0 inches d.b.h. to a 4-inch top.

The precommercial thinnings produced a range of numbers of trees retained, depending on GSL and site index as shown in the following tabluation:

Site index (ft)	Trees per acre retained after precommercial thinning	
	GSL 80	GSL 180
40	515	1,198
50	494	1,159
60	473	1,116
70	452	1,073
80	432	1,030
90	413	988

Only precommercial thinnings were examined due to increased incidence of decay and mortality in partially cut pole-sized stands (Walters and others 1982). In addition, partial cutting results in inferior replacement stands (Jones 1976); therefore, only regeneration by clearcutting is considered.

MODEL RESULTS AND DISCUSSION

Diameter Growth

Periodic diameter growth of aspen is related to stand density, as represented by stand basal area and site quality. Ten-year periodic diameter growth averaged 0.7 inch for all stands sampled in the growth study. At low site indexes, periodic diameter growth averaged 0.6 inch, and at high site indexes the growth rate averaged 0.8 inch. Periodic diameter growth is a linear function of site index, but the effect of site index appears to be much less than for conifers in even-aged stands in the central Rocky Mountains. As with most species that are suited to even-aged management, diameter growth of aspen is greatest at low stand densities, but these low stand densities result in reduced volume yields per unit area. Determination of desirable stand density for managed stands involves consideration of both average tree size and volume production. To achieve appreciable increases in diameter growth, stand basal area must be reduced below 100 ft^2/acre.

Periodic growth rates and changes in diameter resulting from precommercial thinning were examined to determine average tree sizes relative to rotation age and initial stand density. For the range of stand densities and site indexes examined, trees reach average diameters of 5.7 to 9.0 inches at 80 years, and 8.1 to 12.3 inches at 120 years (table 2). On lands of moderately good site index 70, average stand diameters reach 5 inches at 37 to 54 years of age, 7 inches at 64 to 83 years, and 9 inches at 91 to 111 years (fig. 1). Average diameters ranged from 9.6 to 11.3 inches at the maximum rotation age tested, which was 120 years on site index 70 lands. The number of decades required to reach an average stand diameter of at least 5.0 inches for computation of merchantable cubic volume ranged from 4 on thinned site index 90 lands to 7 on unthinned site index 40 to 60 lands (table 3).

Height Growth

Periodic height growth of aspen increases with site index and decreases with age and stand density. Average dominant and codominant height growth follows the site index curves (Edminster and others 1985) with adjustments downward to account for average codominant as well as dominant height (fig. 2). Differences in average dominant and codominant height due to initial stand densities tested are relatively minor. The maximum difference between stands initially thinned to GSL 80 and unthinned stands was 3 ft at 120 years of age across the range of site indexes.

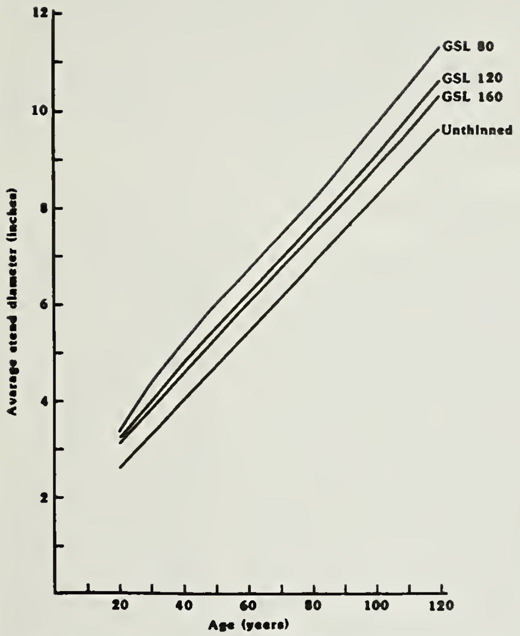

Figure 1.--Estimated average stand diameter of aspen in relation to age and initial stand density on site index 70 lands.

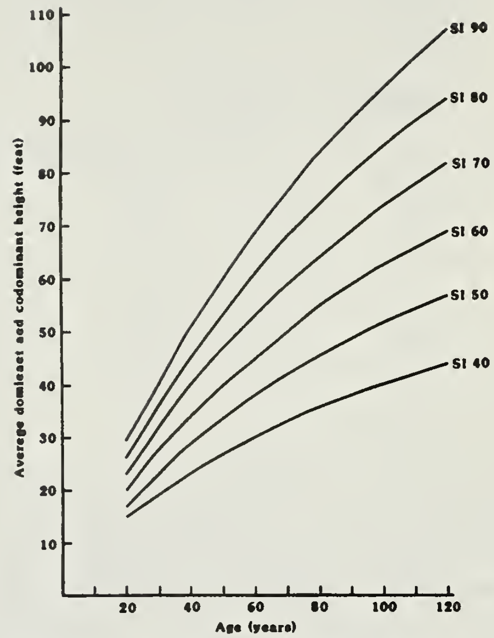

Figure 2.--Estimated average dominant and codominant height of aspen in relation to age and site index.

Table 2.--Estimated average stand diameter (in) and number of trees per acre of aspen at final harvest in relation to initial stand density, site quality, and rotation age

	Growing stock level													
	80		100		120		140		160		180		Unthinned	
Rotation age	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees	Diameter	No. of trees
							Site Index 40							
60	5.9	410	5.6	479	5.4	553	5.2	617	5.1	655	5.0	704	4.5	923
80	7.3	333	7.0	381	6.6	450	6.4	496	6.3	517	6.2	553	5.7	688
100	8.7	271	8.4	304	7.9	361	7.6	399	7.5	417	7.4	438	6.9	527
120	10.1	222	9.8	246	9.3	284	9.0	312	8.9	321	8.7	343	8.1	416
							Site Index 50							
60	6.1	428	5.8	501	5.7	553	5.6	608	5.4	660	5.2	745	4.7	987
80	7.5	358	7.2	406	7.1	443	7.0	478	6.7	530	6.4	599	5.9	758
100	8.9	300	8.6	334	8.5	357	8.4	381	8.1	416	7.7	473	7.1	592
120	10.3	250	10.0	275	9.9	291	9.8	307	9.5	333	9.1	371	8.4	462
							Site Index 60							
60	6.3	429	6.1	497	5.9	563	5.8	615	5.8	648	5.6	713	4.9	1046
80	7.7	371	7.5	417	7.3	464	7.2	498	7.2	519	7.0	561	6.1	813
100	9.1	316	8.9	349	8.7	382	8.6	406	8.6	423	8.4	446	7.5	612
120	10.6	264	10.3	293	10.1	316	10.0	335	10.0	346	9.8	364	8.9	476
							Site Index 70							
60	6.7	412	6.4	496	6.2	553	6.1	620	6.0	667	5.9	721	5.4	974
80	8.1	366	7.8	424	7.6	463	7.5	508	7.4	542	7.3	578	6.8	741
100	9.7	307	9.2	363	9.0	391	8.9	423	8.8	445	8.7	472	8.2	583
120	11.3	258	10.8	298	10.6	318	10.4	347	10.3	362	10.1	388	9.6	467
							Site Index 80							
60	7.0	396	6.8	467	6.5	546	6.4	599	6.2	672	6.2	701	5.6	1011
80	8.6	342	8.4	389	8.0	452	7.8	503	7.6	552	7.6	574	7.0	785
100	10.2	297	10.0	330	9.6	376	9.4	410	9.1	453	9.1	469	8.4	623
120	11.8	255	11.6	279	11.2	312	11.0	337	10.7	368	10.7	379	9.9	493
							Site Index 90							
60	7.4	388	7.1	458	7.0	508	6.8	563	6.8	610	6.4	707	5.8	1051
80	9.0	339	8.7	387	8.6	423	8.4	459	8.4	493	8.0	555	7.2	820
100	10.6	300	10.3	355	10.2	361	10.0	386	10.0	410	9.6	455	8.7	645
120	12.3	259	11.9	288	11.8	308	11.6	327	11.6	343	11.2	375	10.3	508

Table 3.--Estimated number of decades to reach an average stand diameter of at least 5.0 inches in relation to initial stand density and site index

Site Index	Growing stock level 80	100	120	140	160	180	Unthinned
40	5	6	6	6	6	6	7
50	5	5	5	6	6	6	7
60	5	5	5	5	5	6	7
70	4	4	5	5	5	5	6
80	4	4	4	4	5	5	6
90	4	4	4	4	4	4	5

Basal Area Increment

Periodic basal area increment increases with site index and decreases with increasing stand age. For a given site index and stand age, periodic basal area increment is relatively constant for stand ages greater than 40 years over the range of initial stand densities tested. This suggests that basal area growth at the lower stand densities was not redistributed on the fewer residual stems. The pattern of basal area development in relation to age and site index for unthinned stands is shown in figure 3. At a stand age of 120 years, basal area production per acre varied from 149 ft^2 on site index 40 lands to 294 ft^2 on site index 90 lands.

Basal area growth relationships in the model predict growth based on estimated 10-year periodic plot performance. Since mortality is often a clustered event, in both location and time,

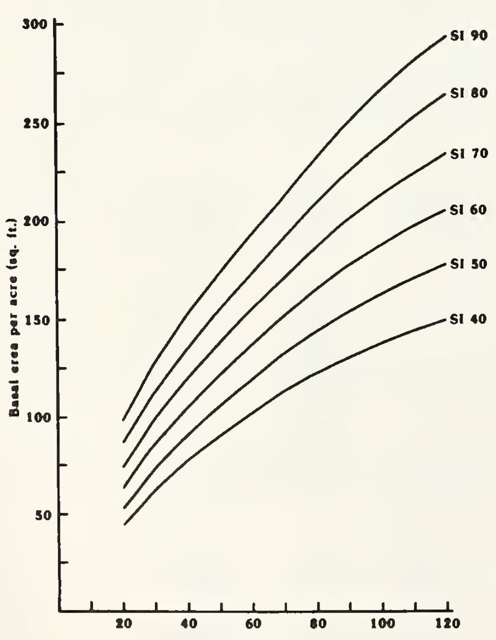

Figure 3.--Estimated stand basal area development in unthinned stands of aspen in relation to age and site index.

samples from a relatively small number of stands over a short time period may not be adequate to accurately predict long-term mortality rates. Further complications arise from the clonal growth and self-thinning characteristics of aspen (Zahner and Crawford 1965). As a result, the prediction of mortality is the weakest component in the aspen growth model.

Merchantable Cubic-Foot Volume Increment

Gross merchantable cubic-foot volume production of aspen is related to stand density, site quality, and rotation age (table 4, fig. 4). Merchantable cubic-foot production was greatest for all site indexes, except site index 40, in unthinned stands. This follows a similar trend for basal area production. The differences in merchantable volume production for a given initial stand density become greater with increasing site index. Although merchantable volume production decreases with reduced GSL's on moderate to high site index lands, tree sizes at higher densities are smaller, and considerably more trees must be harvested to obtain the higher stand volumes (tables 2 and 4). For example on site index 70 land at 120 years of age, unthinned stands produce 6.5 percent more merchantable volume than stands initially thinned to GSL 180, but the unthinned stand contains 20.4 percent more trees which are 0.5 inch smaller in average diameter.

Compared to earlier estimates for aspen in central Utah (Baker 1925), predicted merchantable yields from this study are considerably higher, with differences increasing with increasing site quality. Although direct comparisons are not possible due to different site curves used to index productivity, the following approximate comparisons at stand age 120 years for unthinned stands on a per-acre basis can be made:

Baker Site Class (index height)	Merchantable cubic-foot yields: Baker	Current study
1 (77)	4,600	8,680
2 (67)	3,400	6,540
3 (55)	2,300	4,520
4 (44)	1,700	2,740

Only a small portion of the difference can be explained by the larger utilization standards in Baker's study, where cordwood cubic-foot volume was calculated for trees 6.0 inches d.b.h. and larger to a 5-inch top.

Mean annual increment (MAI) of merchantable cubic-foot volume provides an objective criterion for evaluting growth consequences of different precommercial thinning levels and unthinned stands (Assman 1970). Gross merchantable cubic-volume MAI is related to age, site quality, and initial stand density (fig. 5). For each initial stand density, merchantable cubic-foot volume MAI is greater at each higher site index, and differences become greater with increasing site index. Mean annual increments are increasing through stand age of 120 years. Site indexes 50 and

Table 4.--Estimated gross merchantable cubic-foot volume production per acre of aspen in relation to initial stand density, site quality, and rotation age (trees 5.0 inches d.b.h. and larger to a 4-inch top)

Rotation age	Growing stock level 80	100	120	140	160	180	Unthinned
Years	Thousand cubic feet						
	Site Index 40						
60	0.63	0.61	0.61	0.58	0.56	0.55	0.00[1]
80	1.16	1.17	1.18	1.18	1.17	1.18	1.12
100	1.65	1.68	1.71	1.71	1.71	1.74	1.72
120	2.09	2.13	2.18	2.20	2.19	2.22	2.23
	Site Index 50						
60	1.01	1.00	1.04	1.06	1.03	1.01	0
80	1.76	1.79	1.86	1.92	1.90	1.91	1.91
100	2.50	2.55	2.64	2.72	2.72	2.74	2.80
120	3.17	3.24	3.34	3.42	3.44	3.48	3.57
	Site Index 60						
60	1.39	1.45	1.50	1.55	1.62	1.60	0
80	2.39	2.51	2.59	2.69	2.79	2.79	2.86
100	3.41	3.56	3.67	3.79	3.92	3.93	4.12
120	4.36	4.53	4.66	4.80	4.93	4.95	5.21
	Site Index 70						
60	1.86	1.98	2.02	2.16	2.21	2.28	2.39
80	3.14	3.32	3.40	3.61	3.70	3.82	4.10
100	4.49	4.71	4.81	5.07	5.18	5.33	5.72
120	5.79	6.04	6.15	6.42	6.56	6.72	7.16
	Site Index 80						
60	2.32	2.52	2.64	2.77	2.86	2.98	3.27
80	3.89	4.16	4.35	4.53	4.69	4.85	5.42
100	5.58	5.91	6.15	6.41	6.58	6.78	7.50
120	7.05	7.44	7.78	8.11	8.34	8.57	9.38
	Site Index 90						
60	2.92	3.11	3.34	3.43	3.70	3.71	4.29
80	4.83	5.09	5.40	5.55	5.92	5.99	6.93
100	6.93	7.25	7.62	7.81	8.27	8.38	9.56
120	8.62	9.01	9.42	9.66	10.14	10.37	11.92

[1]Stand merchantable cubic-foot volume is not computed when average stand d.b.h. is less than 5.0 inches.

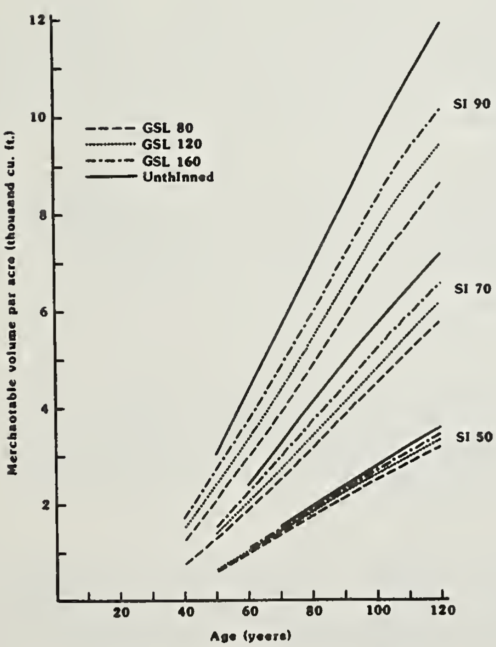

Figure 4.--Estimated gross merchantable cubic-foot volume production per acre of aspen in relation to age, initial stand density, and site index.

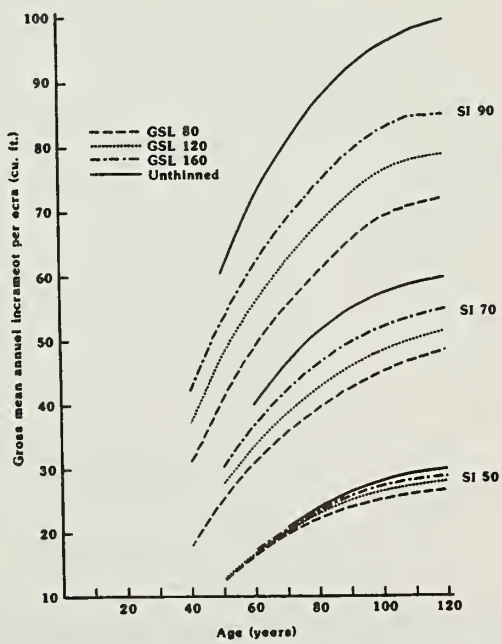

Figure 5.--Estimated gross mean annual merchantable cubic-foot volume increment per acre in relation to age, initial stand density, and site index.

above produce more than 20 ft³/acre annually. Mean annual increment in unthinned stands on site index 90 lands approaches 100 ft³/acre.

A pathological rotation of 90 to 120 years for sawtimber production of aspen in Colorado has been suggested by Hinds and Wengert (1977). Deductions in cubic-foot volume for decay (Davidson and others 1959) were applied to the gross MAI values in figure 5 to determine a reasonable rotation for merchantable cubic-foot volume. Results of the decay study were based on Baker's site classification, and application of the results to the current study is an approximation. Decay deductions for site class 1 were applied to site indexes 80 and 90, class 2 to site index 70, and class 3 to site index 60 and below. Estimates of net merchantable cubic-foot volume MAI's are shown in figure 6. Culmination of net MAI generally occurs between 100 and 120 years, most often at 100 years of age. These results support the recommendations for sawtimber production. Cull resulting from decay varies greatly in stands of comparable age and site quality (Davidson and others 1959; Hinds and Wengert 1977). As a result, the estimates reported here should only be applied to a specific stand with care.

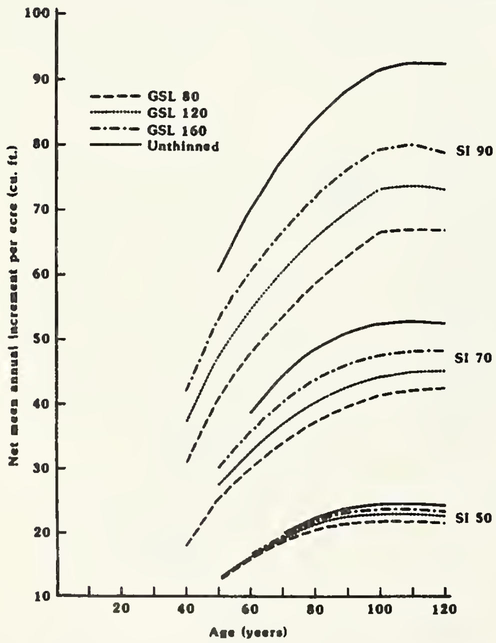

Figure 6.--Estimated net mean annual merchantable cubic-foot volume increment per acre in relation to age, initial stand density, and site index.

MANAGEMENT CAUTION

The growth and yield estimates presented appear reasonable and consistent within the limits of current knowledge based on sampling even-aged natural stands of aspen at a wide variety of stand age, density, and site quality. Comparisons of estimates with actual values from permanent plots in managed and unthinned stands are needed to validate growth relationships and estimates. Thinning studies in a pole-size stand and juvenile stands on three site quality lands are currently underway to provide some of this information.

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INTRODUCTION TO THE PROGNOSIS MODEL--VERSION 5.0

William R. Wykoff

ABSTRACT: The Prognosis Model is a stand development simulator that facilitates forest management planning. Stand development is simulated by predicting the growth of sample trees from an inventory. The stand is assumed to be homogeneous with regard to distributions of species, age classes, site factors, and treatment potential. The model is intended to accommodate all timber types and stand conditions that are encountered in an inventory with growth predictions that are consistent with measured growth. Model versions 4.1 and 5.0 are compared. Version 5.0 outperforms version 4.1 with regard to the permanent sample plots used to assess model validity; in addition, its calibration procedure increases the accuracy of projections and does not depend on growth sampling strategies. Long-range projections of total volume appear to be unbiased, and the model should be useful for long-range planning.

WHAT IS THE PROGNOSIS MODEL?

The Prognosis Model (Stage 1973) is a stand development simulator that facilitates forest management planning. The design of the model was based on five objectives (Wykoff and others 1982):

1. Use existing inventory data as input and produce initial estimates of volume and growth that are consistent with results of standard inventory compilation procedures.

2. Accommodate all timber types and stand conditions that are encountered in the inventory with growth predictions that are consistent with measured growth.

3. Treat stands as the basic unit of management.

4. Incorporate growth of the current inventory into projections.

5. Provide links to other biotic and hydrologic components of the ecosystem and to econometric procedures for selecting appropriate management actions.

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The resulting model simulates stand development by predicting growth, mortality, and the impact of management activities for a sample of trees that comprise the stand. The concept is simple: a list of trees is projected forward in time with sufficient descriptive detail to support decisions that are traditionally based on inventory.

The current formulation of the model, as calibrated for the Inland Empire, predicts d.b.h. increment, height increment, survival, and change in crown length for individual trees for variable length periods. There are also linkages to interactive population dynamic models for specific pests that can modify the predicted growth and survival or the perceived vigor of the trees. At the end of a growth prediction cycle (usually 10 years), tree volumes are computed, stand density and yield statistics are compiled, scheduled management activities are simulated, and a new cycle begins.

Although the conceptual framework outlined above is simple, the Prognosis Model is admittedly complex. The Inland Empire has a relatively rich species diversity, considerable geographic relief, and a history of recurrent insect and disease problems, catastrophic fires, and less-than-enlightened management. A simple model would be inadequate to address the spectrum of current management problems in the context of this diversity; however, the model was designed to minimize the impact of complexity on the user. Management actions are specified with relatively straightforward keywords, and the output includes displays of stand development that vary in resolution from a yield table to a complete list of the attributes of all trees in the stand. The first production version of the Prognosis Model, version 4.0, was released in 1981; version 4.1 was subsequently released with changes to the small-tree growth models; version 5.0 was released in the summer of 1984. The options described in the user's manual for version 4.0 (Wykoff and others 1982) are applicable to version 5.0, and new options are specified in a supplement to the user's guide (Wykoff in preparation). This paper briefly describes and contrasts the function and behavior of versions 4.1 and 5.0.

WHAT MANAGEMENT ACTIVITIES MAY BE SIMULATED?

In version 4.1, management options are limited to activities that reduce stocking of existing stands (Wykoff and others 1982). A great deal of flexibility is permitted in determining the trees to be removed, and the growth response varies

with the character of the residual stand. For most thinning options, the date of an entry must be specified by the user.

These same features have been included in version 5.0. In addition, an Event Monitor (Crookston in preparation) may be used to schedule activities contingent on stand characteristics rather than date. As a simple example, a stand may be automatically thinned to 100 ft^2 of basal area any time that the stand density exceeds 140 ft^2. In fact, the event that triggers an activity can be defined to simultaneously include specified values for many stand characteristics so that complex strategies can be simulated.

Along with the Event Monitor, a new biological model has been added to version 5.0 to predict the establishment of regeneration following site disturbance. This addition permits the evaluation of reforestation strategies (Ferguson and Crookston 1984). It may also be used to include the influence of ingrowth competition following thinning.

Versions 4.1 and 5.0 are both programmed to link readily to "extensions" that simulate the dynamics of specific pest populations and their impact on the stand. At present, a tussock moth model is available (Monserud and Crookston 1982), and western spruce budworm and mountain pine beetle models are under development. These extensions can be used to test the impact of control strategies on the development of the stand and of the pest population. In addition, the program for computerized help for economic analysis of Prognosis output, CHEAPO (Medema and Hatch 1982), has been revised and rereleased for version 5.0.

Also under development is a model that predicts the distribution of shrub species and the percentage of cover (including shrubs and trees) by vertical strata within the stand (Moeur in preparation). This extension facilitates linkage to models that predict wildlife populations or water production from the estimates of forage availability and cover density.

Finally, there are two algorithms under development that will further enhance the flexibility of version 5.0. The first is an uneven-aged management algorithm that, in conjunction with the Regeneration Establishment Model, permits simulation of all-age management strategies (Lyons in preparation). The second is the Parallel Processing System, which can project up to 200 stands simultaneously. With this system, contagious effects of pests can be considered, and harvests can be planned to meet watershed and visual constraints. Also, when used with the Event Monitor, the Parallel Processing System can efficiently simulate a rather complex decision tree (Crookston in preparation).

CHANGES IN GROWTH MODELS

The differences between the growth models in versions 4.1 and 5.0 reflect an attempt to make the individual tree projections more sensitive to differences in stand structure. The most important changes are in models that predict height and d.b.h. increments and changes in crown ratio for small trees (d.b.h. $\leq$3 inches) and mortality rates for all trees.

Small-Tree Height and Diameter Increment

In version 4.1, diameter increment is predicted with the same model for all trees, and there is no feedback between the small-tree height increment and d.b.h. increment models. As a result, height and d.b.h. predictions may be inconsistent, resulting occasionally in trees that are extremely tall for their d.b.h.'s. In version 5.0, small-tree diameter increment is predicted directly from height and height increment, thus assuring consistency.

In addition to the inconsistency between height and d.b.h. increment predictions, version 4.1 height increment predictions are not dependent on any measure of the competitive status of a tree relative to its neighbors. Thus, there is little in the model to promote the expression of dominance, and the model does not reproduce the within-stand variation in height and diameter that is typically found in young managed stands. In version 5.0, this problem was mitigated by adding a relative size term to the small-tree height increment model. Predictions of height and d.b.h. increment are, as a result, sensitive to both social status and overall stand density (fig. 1).

Small-Tree Crown Ratio

With the change in strategy for predicting d.b.h. increment, none of the growth predictions for small trees are dependent on crown ratio. Assignment of crown ratio is consequently delayed until the tree attains a 3-inch diameter. Crown ratio is then predicted from species, d.b.h., height, and stand basal area. Thereafter, crown ratio change is predicted as in version 4.1.

Mortality

In version 4.1, a basic mortality rate is predicted from species and d.b.h. The basic rate is then adjusted to reflect the effects of stand density. Adjustment factors are based on yield tables (Haig 1932), published data on carrying capacity by habitat type (Pfister and others 1977), analysis of Northern Region timber management planning inventories, and some judicious guessing.

The version 5.0 models are dependent on species, d.b.h., d.b.h. increment, relative diameter (d.b.h./mean stand d.b.h.), and stand basal area (Hamilton in preparation). The explicit density and relative size terms have eliminated the need for most of the guesswork that was included in version 4.1. As stand density increases, mortality rates increase for all trees; the dominant trees and subordinate trees that exhibit rapid growth have the best chance of survival. The new formulation results in reduced mortality rates following stocking reduction or treatments that otherwise enhance the growth of the residual trees.

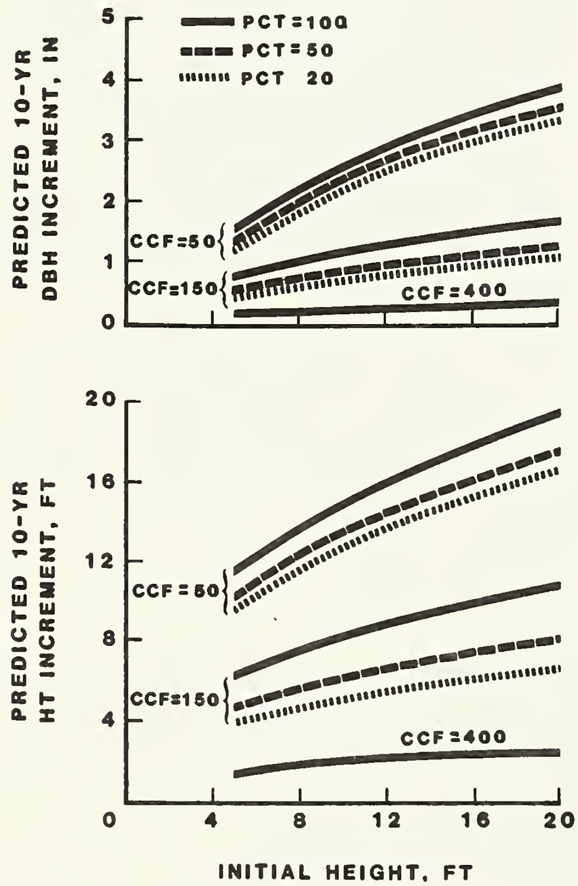

Figure 1.--In version 5.0, small-tree height and diameter increment predictions are sensitive to stand density and relative size. Curves are for Douglas-fir growing on a Thuja plicata/Clintonia uniflora habitat type at 3,700 feet elevation in the Clearwater National Forest.

Large-Tree Diameter Increment

Changes to the large-tree d.b.h. increment model are somewhat more subtle. In version 4.1, the relative size term has about the same effect on the d.b.h. increment prediction regardless of tree size. In version 5.0, a d.b.h.-relative size interaction term was added to decouple the size and relative size effects. Thus, an increment prediction for a small tree in one stand is more strongly affected by relative size than is the prediction for a larger tree in a different stand, even though the two trees are at the same relative position in the d.b.h. distribution within their respective stands. As a result of this change, the maximum in the increment curve, as related to diameter, shifts toward larger d.b.h. with increasing density and decreasing percentile in the stand basal area distribution (fig. 2). The net effect is smaller d.b.h. increment predictions for small trees at high densities.

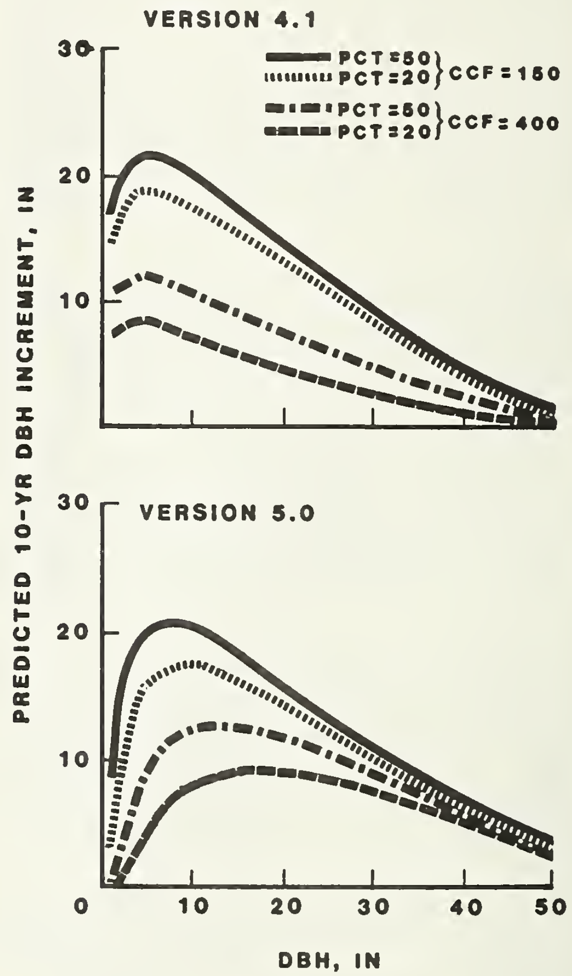

Figure 2.--Large-tree diameter increment models are slightly different in version 5.0. The most notable differences in predictions are for subordinate trees growing in dense stands. In version 5.0, the maxima in the increment curves shifts toward larger d.b.h. as crown competition factor (CCF) increases, and percentile in the stand basal area distribution (PCT) decreases. Stand conditions are the same as for figure 1.

Compression and Calibration

There are two additional modifications to version 5.0 that do not relate specifically to model formulations but do impact performance. First, a regression procedure was adopted to adjust models

for differences between predicted and inventoried growth rates. The Prognosis Model was designed to accommodate considerable variation in the inventory sampling design; however, the version 4.1 calibration procedure only gives unbiased adjustment factors if growth sample trees are selected with probability proportional to tree basal area. The new calibration procedure eliminates bias that results from differences in ways that growth sample trees are selected. The only obvious difference in performance is the requirement for five growth samples for a species in order for the adjustment to take place. This requirement applies to both the large-tree d.b.h. and the small-tree height increment models. In version 4.1, only two growth samples were needed.

The second modification is a compression procedure that permits records to be combined into groups that are similar with regard to variables that strongly influence growth projections. The compression procedure (Stage and others in preparation) is used to create space for new records when the establishment model is called to eliminate records that, due to thinning or mortality, are no longer significant, or to reduce the number of tree records so that projections are less costly but retain as much as is possible of the original variation in tree characteristics.

MODEL PERFORMANCE

A number of "benchmark" simulations were designed to help evaluate model performance. As no standards are available, rigorous analysis of the results of these simulations was not attempted. Comparison of benchmarks, however, illustrates differences between the behavior of versions 4.1 and 5.0 and permits subjective evaluation of model changes.

As discussed earlier, major changes were made in the small-tree height and d.b.h. increment models in version 5.0. The impetus for these changes was the perceived insensitivity of version 4.1 to differences in stand density and structure. In stands of small trees there was insufficient variation in the distribution of within-stand diameters and too little difference in average stand diameter across a wide range of spacings for stands of the same age. With version 5.0, as illustrated by projections for a white pine spacing study (figs. 3 and 4), there is greater spread in the within-stand diameter distribution and wider spacings result in significantly larger average stand diameters.

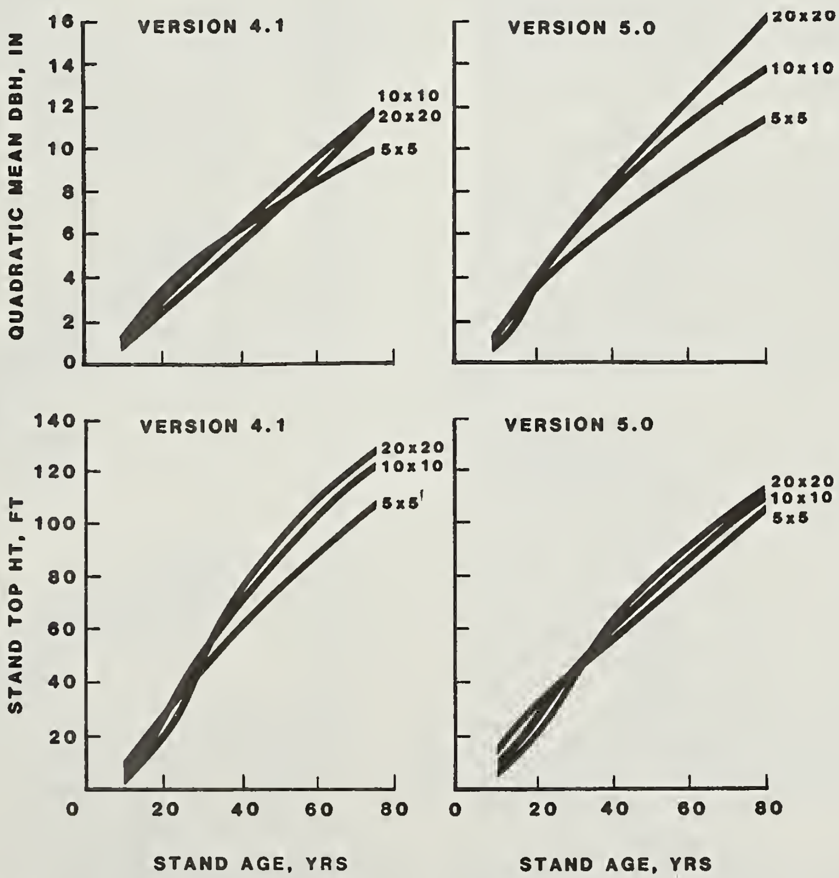

Figure 3.--When projections are made for different initial spacings, version 5.0 produces more variation in quadratic mean d.b.h. and less variation in stand top height than does version 4.1. Curves are for western white pine growing on a Tsuga heterophylla/Clintonia uniflora habitat type at 3,400 feet elevation on the Coeur d'Alene National Forest.

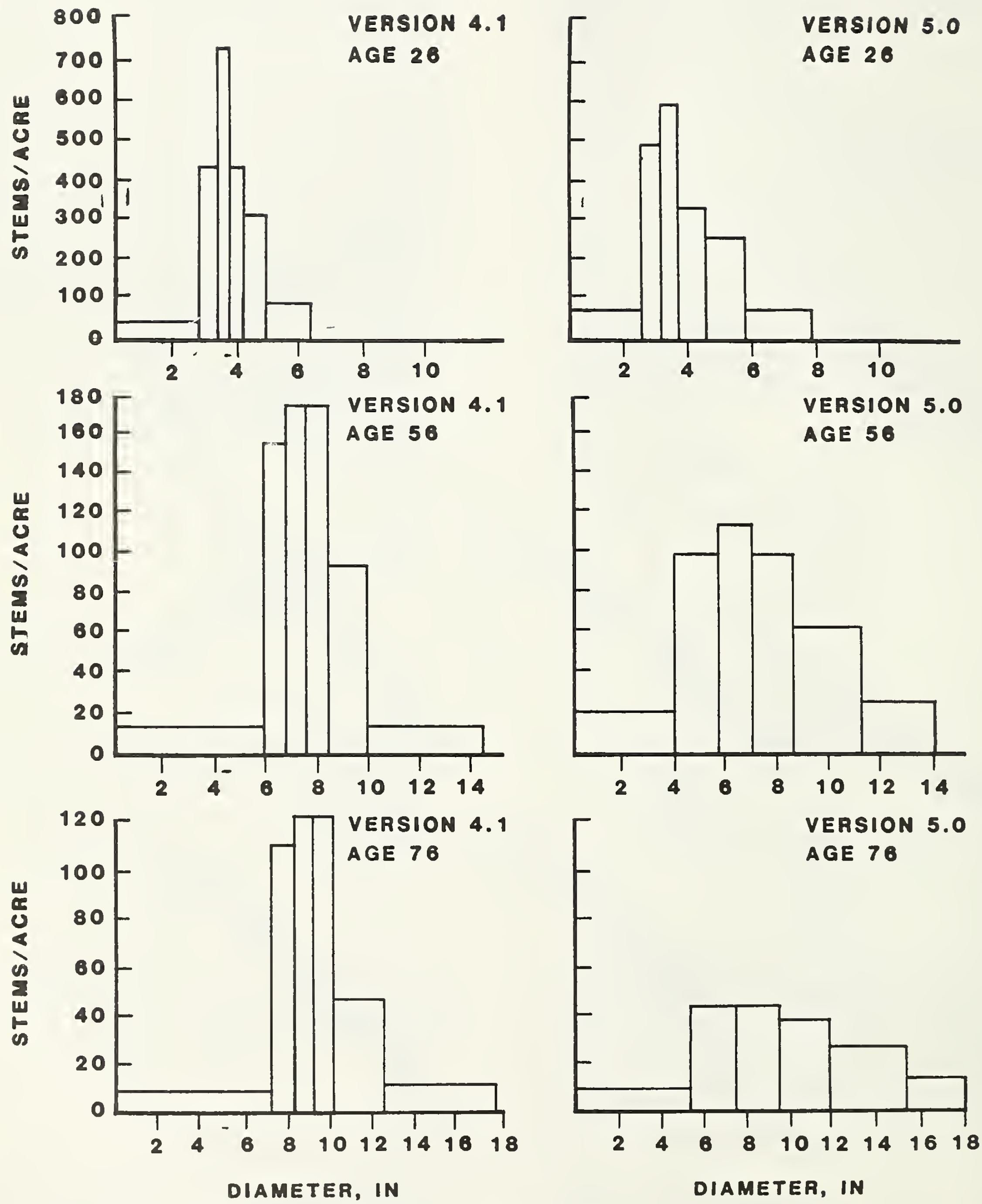

Figure 4.--Version 5.0 projections result in greater variation in within-stand d.b.h. than do version 4.1 projections. Stand conditions are the same as for figure 3. Distributions shown are for the 5- by 5-foot initial spacing.

The changes in the model for small trees improved the discrimination of site quality. When Douglas-fir plantations were simulated with version 4.1 for radically different sites (ranging in quality from a Thuja plicata/Clintonia uniflora habitat type at 3,700 feet elevation in the Clearwater National Forest to an Abies lasiocarpa/Menziesia ferruginea habitat type at 5,200 feet on the Lolo National Forest), there was only a 17-foot difference between top heights at a stand age of 110 years. With version 5.0, this difference increased to 35 feet (fig. 5). Projections with both versions were made without calibrating the growth models to match past growth. Otherwise, the range of apparent site quality could be greater; the use of inventory growth data is an important design feature of the model that helps resolve variation in site quality within a habitat type. Projections based on average growth rates cannot reflect the range of variation in site quality evidenced in nature.

Other benchmark simulations have been designed to exercise various model features such as compression, thinning, and regeneration establishment. These simulations are distributed with the program and will be valuable for user assessment of model performance now and following future changes. As earlier indicated, however, these comparisons do not address model validity.

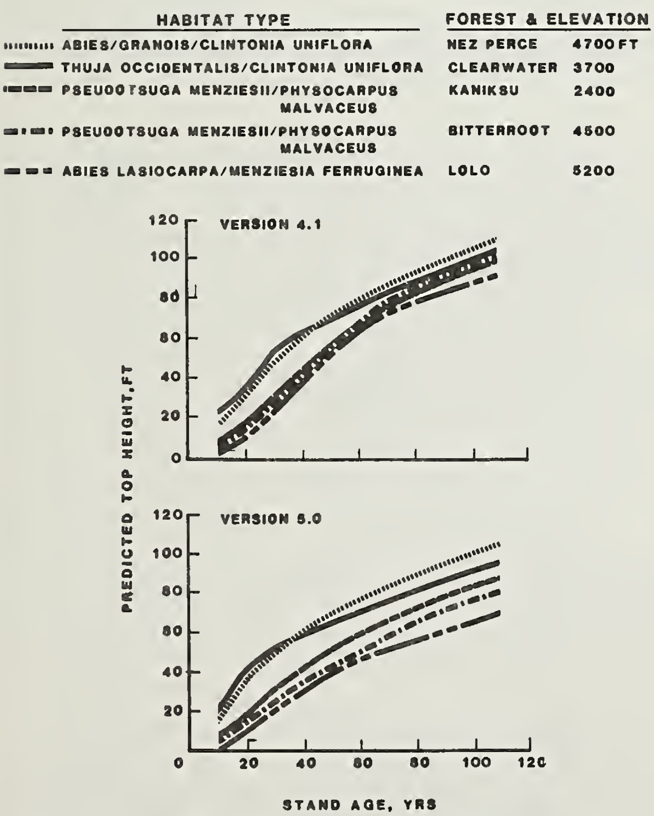

Figure 5.--Comparison of top height projections for versions 4.1 and 5.0 with Douglas-fir planted on a variety of sites. Projections began with a list of tree records that was generated by the Regeneration Establishment Model for the indicated site conditions.

An independent evaluation of model performance and comparison of versions is nearing completion. This comparison is based on a collection of 119 permanent sample plots that are located on relatively productive sites in northern Idaho. The plots have been measured every 5 to 10 years for total periods ranging from 10 to 60 years (mean 34.5 years). In these analyses, errors due to mortality predictions were isolated from errors due to increment predictions by suppressing the mortality function and removing only the trees that actually died at the time they were recorded as dead.

The version 4.1 calibration procedure was among the early casualties of the evaluation. As was earlier described, this calibration procedure was optimized for inventory systems in which trees were sampled for growth in proportion to their basal area. Fixed-area plots were used for the model evaluation and all trees were measured for growth, resulting in an underestimate of model adjustments. Thus, calibrated projections produced poorer estimates of future stand attributes. The calibration procedure was replaced in version 5.0 with a procedure that is more tolerant of differences in growth sampling methods.

Considering the average differences between observed and predicted values for stand attribute in the permanent sample plots, version 5.0 projections of stand attributes are less biased and more precise than predictions from version 4.1 (table 1). In this sense, the version 5.0 formulations represent a substantial improvement.

It is also evident that version 5.0 projections are improved by calibration. The 95 percent confidence intervals constructed about the mean differences between predicted and observed attributes (table 2) show that predictions of total cubic-foot volume are unbiased and that the mean difference between observed and predicted volume is probably less than ±10 percent of the observed change. This level of accuracy is probably sufficient for long-range planning.

Further, when errors attributable to mortality are removed from the analysis, the "no calibration" projections give a good indication of the performance of component growth models. Predictions of quadratic mean d.b.h. are slightly biased, but explain 92 percent of the variation observed in the test data. In this case, explained variation is measured by the ratio of the variance of the bias in predicted change (predicted change minus observed change) to the variance of the observed change. Using this definition, if the average change in stand attributes for the collection of plots were known in advance and used as a model to predict changes, the predictions would be unbiased but none of the observed variation in the system would be explained.

Predictions of top height are unbiased as well and explain 75 percent of the observed variation (tables 2 and 3). Calibration leads to further improvement in explained variation of both attributes, reduces the bias in predicted quadratic

Table 1.--Comparisons of observed change in stand attributes showing bias associated with various estimation procedures[1]

Source of estimate	Stand Attribute: Quadratic mean d.b.h.	Top height[2]	Basal area per acre	Total volume
	Inches	ft	ft^2	ft^3
Observed change	4.1 (1.98)	32.2 (19.0)	36.6 (52.8)	2,898 (2,031)
Version 4.1, predicted mortality, no calibration	.45 (1.22)	-1.19 (10.5)	66.3 (48.8)	2,369 (2,203)
Version 5.0, predicted mortality, no calibration	.27 (.95)	2.32 (10.2)	31.1 (52.0)	1,140 (2,058)
Version 5.0, predicted mortality, calibration	-.17 (.82)	-2.89 (10.1)	11.0 (43.8)	-17 (1,588)
Version 5.0, observed mortality, no calibration	.28 (.57)	.52 (9.4)	9.71 (21.6)	422 (1,325)
Version 5.0, observed mortality, calibration	.03 (0.44)	-2.87 (9.2)	1.66 (13.6)	-118 (866)

[1]Standard deviation about bias is given in parentheses. Estimates are based on 119 plots with an average measurement period of 34.5 years.

[2]In version 4.1, top height is defined as the average height of the largest 30 percent of the trees in the stand by basal area. In version 5.0, the more traditional definition, height of the largest 40 trees per acre by d.b.h. is used.

Table 2.--Ninety-five percent confidence intervals about the mean error in prediction of change for the stand attributes and estimation procedures shown in table 1

Source of estimate	Stand attribute: Quadratic mean d.b.h.	Top height	Basal area	Total volume
	Inches	ft	ft^2	ft^3
Version 4.1, predicted mortality, no calibration	(0.23, 0.67)	--[1]	(57.4, 75.2)	(1,967; 2,770)
Version 5.0, predicted mortality, no calibration	(0.10, 0.44)	(0.46, 4.18)	(21.6, 40.6)	(765; 1,515)
Version 5.0, predicted mortality, calibration	(-0.32, -0.02)	(-4.73, -1.05)	(3.0, 19.0)	(-306; 272)
Version 5.0, observed mortality, no calibration	(0.18, 0.38)	(-1.19, 2.23)	(5.79, 13.63)	(181; 662)
Version 5.0, observed mortality, calibration	(-0.05, 0.11)	(-4.55, -1.19)	(-0.82, 4.14)	(-276; 40)

[1]Due to the change in definition for top height, the initial value for comparison with version 4.1 was unknown as of this writing. Consequently, the confidence intervals could not be computed.

Table 3.--Proportion of the total variation[1] in stand attributes for the 119 permanent sample plots that is explained by various estimation procedures

Source of estimate	Variation explained by attribute (Percentage)			
	Quadratic mean d.b.h.	Top height	Basal area per acre	Total volume
	Inches	ft	ft^2	ft^3
Version 4.1, predicted mortality, no calibration	62.0	--[2]	14.6	-17.7
Version 5.0, predicted mortality, no calibration	77.0	71.2	3.0	-2.7
Version 5.0, predicted mortality, calibration	82.8	71.7	31.2	38.9
Version 5.0, observed mortality, no calibration	91.7	75.5	83.3	57.4
Version 5.0, observed mortality, calibration	95.1	76.6	93.4	81.8

[1]Computed as $1 - \dfrac{\text{Variance of bias in predicted change}}{\text{Variance of observed change}} \cdot 100.$

This number is negative when the variance of the bias in predicted change is greater than the variance of the observed change.

[2]Could not be computed--see footnote to table 2.

mean d.b.h., but increases the bias in predicted top height. There is, however, still considerable unexplained variation in the permanent sample plot comparison. It is somewhat disturbing that nearly 30 percent of the predictions were biased by more than 50 ft^3/acre/year (fig. 6), and this apprehension is compounded by the relatively small proportion (39 percent) of variation in total volume that is explained by the model.

There are factors to consider in defense of the model. First, as total length of projection increases, the accuracy of the volume estimates increases (fig. 6). Although we prefer to visualize stand development as a smooth progression relative to time, the processes of growth and mortality are subject to the erratic and intertwined effects of pests, climate, and site. In reality increment and mortality are both clustered in time and space. Errors for short-run projections may be large, but for long-run projections, irregularities average out resulting in more accurate predictions.

Second, when mortality is removed as a source of variation, estimates of future stand attributes substantially improve. It appears that the increment models are sensitive to the diverse stand structures that result from irregular patterns of mortality. We therefore expect the increment models to perform adequately when stand structure is changed through management. Thus, the model should give reasonable predictions of thinning responses.

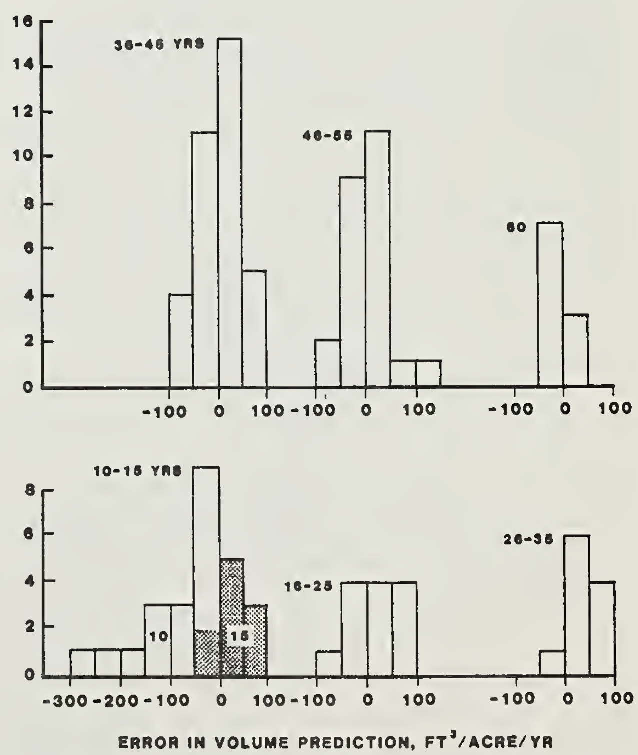

Figure 6.--Distribution of the permanent sample plots used for model evaluation by error in total cubic foot volume predictions and length of projections.

CONCLUSIONS

Version 5.0 outperforms version 4.1 with regard to the permanent sample plots used to assess model validity. In addition, the version 5.0 calibration procedure increases the accuracy of projections and is not dependent on growth sampling strategies.

Long-range projections of total volume appear to be unbiased, and the model should be useful for long-range planning. Growth relations are sensitive to stand structure and density and should give adequate representation of response to management. There remains, however, considerable unexplained variation in mortality.

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DEVELOPING MULTIRESOURCE MODELS FOR THE LAND MANAGEMENT PLANNING PROCESS

Lawrence D. Garrett

ABSTRACT: Changes in forest policy and law have placed greater emphasis on multiresource management and on techniques to ensure its efficiency and effectiveness. Although lack of data has impeded progress in multiresource modeling, conceptual and prototype models are being developed. For the models to find expanded use in land management planning, their development must be based on sound scientific principles and reflect the needs of management. Managers and analysts using the models must do so within constraints specified in their development.

INTRODUCTION

Forestry professionals must continue to develop better methods for managing the productivity and use of the Nation's forest resources. Emphasis is needed in research, development, and application. One area requiring additional research effort is modeling multiresource response to alternative management strategies (Hartgraves 1981). Better response functions are needed to describe an individual resource reaction to different alternatives. But, more important, better systems approaches are needed at the forest level to project the interrelated response of several resources to a given management alternative.

The multiresource concept is not new. Foresters have been and are continuing to manage for multiple benefits. Today, however, more stringent constraints are imposed on planning and management due to changing law, special interests, and policy. The forester must be able to provide a clearer picture of expected outcomes from a management alternative prior to implementation.

A brief overview of management direction reveals the critical need for multiresource evaluation and projection techniques, and for greater emphasis on analysis and interpretation of multiresource data for deriving multiresource models and/or systems.

Paper included in this proceedings by invitation.

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In 1960, the Multiple Use-Sustained Yield Act identified the multiple uses served by the National Forests (USDA 1978). However, the problem of determining procedures for allocating resources, such as timber and recreation, among competing interests was not resolved in the Act.

Succeeding acts made the responsibility more explicit: The Renewable Resources Planning Act (RPA) of 1974 assigned responsibility to the Chief of the Forest Service to periodically assess the supply and demand for forest and range resources (USDA 1976). In 1976, an amendment to the RPA, titled the National Forest Management Act (NFMA), outlined systematic methodology for planning the allocation, use, and future productivity of the National Forest System's multiple resources (USDA 1979). The amendment addresses the need to develop standards and methodologies for improving multiresource management planning and monitoring of the National Forest System.

Whereas Forests have traditionally been managed by a number of functional resource plans, the new process requires each Forest to prepare a single, integrated plan developed by an interdisciplinary team of forest specialists. The process is described as a nationally controlled and directed program which attempts to:

1. Determine for each Forest the operational and biological feasibility of achieving specified target output levels under given budgetary, operational, and production capacity constraints.

2. Determine production targets at Regional and Forest levels which minimize the total cost of production (economic, social, and environmental costs are considered) (Hartgraves 1981).

To accomplish this intense planning process requires data sets on all resources being managed at the forest level. Timber inventories are available and have proven useful in evaluating this resource in the planning process. However, there are no national continuous inventory methods applied for developing data bases on the many other resources currently managed.

Data bases developed by research in several areas of the United States could be used for developing prototype systems. Existing research data bases, used in concert with continuous forest inventory and other forest inventory data, do afford a starting point for development and testing of multiresource projection systems. Such systems will be plagued by data weaknesses. However,

they should be far superior to several methods presently available and in use.

ADAPTING MULTIRESOURCE MODELING TO FOREST PLANNING

The process of developing multiresource projection techniques is attainable, but at various levels of efficiency and effectiveness. As noted, many of the difficulties relate to data availability. Many National Forests have little multiresource data and must rely on estimates that cannot be supported by any level of statistical analysis. Other Forests with ongoing data inventory and/or cooperative research programs may have sufficient multiresource data to develop statistical models for several resources.

No Forest has sufficient single- or multiresource data from inventory to develop absolute values for population parameters. Yet, if scientifically valid procedures are applied to even partial data bases, more efficient and effective methods can be developed for understanding and projecting multiresource outputs.

Currently, we have only begun to investigate multiresource models for projecting resource outputs under differing management alternatives. Efforts by Boyce (1977) were successful in developing DYNAST-MB, a multiresource projection model for evaluating multiple benefits for eastern hardwood forests. This system is now being expanded for broader use in land management planning.

Research efforts in the Southwest have been effective in developing a prototype multiresource model for projecting multiresource outputs from ponderosa pine forests and the pinyon-juniper woodland type (Rogers and others 1981). The research program was designed to evaluate tradeoffs in multiresources that result from implementation of differing forest management alternatives. Research outputs have been expressed in management guidelines and analytical models.

Development of the prototype multiresource model was dependent upon a data base obtained from 20 years of research. The data were taken from over 40 research watersheds studied to determine impacts of management treatments on timber, range, wildlife, water, sediment, and scenic beauty.

Results of the long-term research effort in the Southwest revealed aspects of multiresource modeling that could be helpful to researchers undertaking similar efforts. These aspects involve defining appropriate analytic technique and model structure in model development, as well as defining appropriate procedures for model use after development.

Developing Multiresource Models

Efforts should begin with evaluations of existing data that can be utilized in such an effort. Where insufficient and/or unreliable data exist, assessments should be made of minimal cost approaches to structuring of data bases that could be effective in developing resource models or calibrating models transported from other areas. Even before data bases are in place, conceptual multiresource models can be structured to address specific problems. Many systems analysis and operation research techniques exist for development of models or systems. Linear programming, goal programming, integer programming, nonlinear programming, dynamic programming, simulation, queuing theory, decision theory, and network theory can be used, depending upon the problem addressed and data available.

Simulation is used by modelers because they can accomplish many objectives without extensive data bases. Bare (1971) gave several reasons for use of simulation. These include: (1) the technique is versatile, enabling it to be used for a variety of purposes; (2) models and systems can be constructed to tailor fit the situation; (3) models and systems can be built around an existing data base without requiring major data gathering efforts; (4) "quick and dirty" models can be developed with short lead times to provide timely information; and (5) "quick and dirty" solutions are often satisfactory when one understands that the actual implementation of the prescribed plan is likely to be modified somewhat on the ground.

Any model developed for forest planning should respond to the manager's needs to meet the requirements of NFMA, or more generally implement effective management practice. The following outline illustrates general areas of capability that are important in multiresource models developed for forest planning.

--A main program to control the simulation and call other components in proper sequence. It should provide capability for simulating several management alternatives during a single program execution.

--An input and initialization component that reads user instructions and a description of the current forest stand. An interactive question-answer dialogue is most effective, and enables the user to select different tree species, choose among optional models for some species, and define variables that describe overstory, understory, forest floor, and environment.

--Resource projection components to simulate resource outputs on an annual time step. Simulations should include:

1. forest growth and yields;
2. herbage yields and carrying capacity;
3. forest floor, snag, log, and debris accumulation and decomposition;
4. water yields;
5. soil loss; and
6. wildlife habitat.

--Activity simulators to provide the manager with methods of simulating the implementation of various forest prescriptions under differing management alternatives. Areas of simulation capability should include various methods of tree cutting, regeneration, salvage cutting, range improvement, prescribed burning, site preparation, and fuelwood removal.

--Output and summary component simulators to provide summaries of the effects of treatments on resources. Standard output should include information required in forest planning. Optional outputs could include detailed summaries of individual resource and activity impacts.

Implications to Management

The benefits that multiresource research and modeling can offer to forest management planning are many. Most important is the ability to evaluate complex tradeoffs that occur in a forest area when management actions are taken. Because discerning publics are scrutinizing all potential impacts of planned change, it is necessary to identify both the individual and the interactive impact of a management action.

With the important need and opportunity to improve our capability, are we gaining ground? And if not, why not, and what can be done?

Efforts are being made, and some are extensive. The Forest Service has adopted FORPLAN, a linear program resource allocation model, for use on all National Forests (Gilbert and others 1983). Using information from analysts or multiresource projection models, FORPLAN can provide the manager with guidelines as to the best management alternative to pursue.

Analytic capability is also being improved through application of new hardware systems. Compatible systems are currently being manufactured for assignment to each National Forest. In addition, Federal and university research is ongoing to improve knowledge of how individual resources react to various management actions.

Federal and university research is also developing new resource projection models for use in planning and management. As noted, extending these efforts to multiresource modeling is occurring, but at a slower pace. The availability of effective multiresource data impedes progress, but probably just as important are the actions of researchers and managers.

Researchers have too often taken the "ivory tower" approach to modeling. The results are usually not an appropriate solution to the manager's problem. Managers then become skeptical of the real contribution modeling can make to management science.

Grayson (1973, 1975) indicated that managers may be reluctant to support or use these types of efforts because: (1) analysts take excessive time to respond to managerial requests, (2) data needed for many models are inaccessible even after models have been constructed, (3) many managers are still uncomfortable and not familiar with systems and models and are resistant to use them, and (4) many analyst groups produce systems and models that barely resemble the real world.

Yet it is a foregone conclusion that managers must use analytical models and systems to keep pace and research must assist in their development. To do the job effectively requires a unique level of understanding and cooperation from each. It also requires that the mystique of computers and modeling be resolved and cast in the same light as calculators and arithmetic. They are simply another stage of development.

Managers and researchers alike must be aware of the difficulties associated with model development. Further, identified weaknesses and strengths must be the guidelines for their use. In this regard, both the researcher and manager have responsibility for their correct use.

DIFFICULTIES IN MODEL DEVELOPMENT

It must be understood by both the manager and the researcher that multiresource models are abstractions of the real biological world. Developing an analytical model to accurately describe one wildland process such as timber growth is difficult. The task is more complex when many resource models are linked, as in multiresource modeling.

When a model must be further constrained to conform to a manager's requirements of brevity and simplicity, difficulties increase. That is, the model must capture the real world in the smallest number of variables possible, and with a minimal amount of complexity in the variable interactions. Normally, biological processes are not simplistic, and actions to simplify or constrain the model often increase error.

The researcher is always limited by his available data in structuring a model that is biologically reasonable and also affords prediction efficiency. Most established guidelines constrain the number of variables contained in the model to a smaller subset, which will provide the predictive efficiency appropriate to its intended use. The inclusion of all variables known to affect the natural process is normally illogical due to restricted data availability, marginal increases in predictive efficiency, and increased cost with increased data requirements and model complexity.

Once the researcher has developed a model, two factors limit his ability to make the model useful to the manager:

1. The accuracy with which the developed model defines the biological processes being evaluated.

2. The accuracy with which data selected for model development represent the total variation in the environment under evaluation.

If the manager wishes to transport a model to an area different from where it was developed, the researcher is faced with additional problems. The model's usefulness then depends upon the extent to which parameters that accurately describe natural processes in the new area differ from areas where the model was developed. That is, are the same parameters appropriate and adequate? And would the relationships among model parameters and structure be the same in the new area? Usefulness also depends upon the extent to which data differ, both in diversity and variability.

USING MODELS CORRECTLY

Models, developed with acceptable procedures, are sometimes misused. Correct use is critical, and it relates not only to how and where the model is applied, but also to how the manager or analyst uses the outputs. Models can be expected to fail on some occasions due to oversimplification of assumptions and relationships, rarely encountered situations that have not or cannot be properly modeled, or extreme conditions that have not been considered. Modelers are obligated to specify these constraints, and users must understand their significance. If managers deliberately use models or systems in questionable applications or blindly use outputs that are questionable, the true utility of models has been destroyed.

There is clearly an obligation to the researcher to clarify the capabilities and limitations of his modeling efforts. It is his responsibility to determine the quality of his predictions and present any constraints on the models which are appropriate.

It is not the responsibility of science or scientists to define a model as good or bad. There is no absolute test as to the validity or accuracy of a model, but only subjective judgments based on the proposed use of the model, the acceptable level of errors, the availability of alternative models, and other user-related practical considerations.

Given the information on a model's capabilities and limitations, the manager must decide on its use. Once he has decided to use the system, he has a responsibility to use it within the limits of its design and evaluation.

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INVENTORY PARAMETERS FOR VOLUME ESTIMATION AND PROJECTION

David R. Bower

ABSTRACT: Traditional forest inventory parameters are described in relation to volume or product estimation and in relation to growth projection. Parameters or attributes described include (1) stand table with impact on products and value, (2) level of stocking with impact on present and future volume, (3) spatial distribution of stocking with impact on volume, (4) dominant height with impact on present and future volume, (5) tree form with impact on volume, and (6) competing species with impact on volume growth.

INTRODUCTION

This paper describes traditional forest inventory parameters, or attributes, useful for volume estimation and projection and shows how omitting an attribute or inaccurate measurements impact volume estimates. Examples are taken from loblolly pine plantations.

STAND ATTRIBUTES

Rustagi (1979) distinguishes between primary stand attributes, collected at time of inventory, and secondary stand attributes, predicted or calculated from the primary attributes. Examples of primary attributes are stand age, dominant height, basal area, trees per unit area, average diameter, and crown ratio. Secondary stand attributes include site index (unless the height of dominants is measured at base age), relative density, and volume per acre.

MacLean (1979) describes the use of treatment opportunity stratifications, for example, stratifying clumps within the stand as candidates for precommercial thinning. Other treatment stratifications for a setting include brush control, fertilization, or commercial thinning.

Depta (1974) summarizes attributes which can be used to generate stand tables. His data inputs include basal area per acre, number of trees per acre, minimum d.b.h., quadratic mean d.b.h., maximum d.b.h., the associated height for each d.b.h., and stand form (even or uneven aged).

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The importance of stand table estimation will be discussed in a later section.

Several attributes in addition to diameter and height have been suggested for tree volume estimation. A taper system by Dell (1979) uses crown ratio for predicting product yield, whereas Matney and Sullivan (1979) report that form quotient is the most important variable for volume estimation after d.b.h. and height. Frazer (1979) discusses stratification by height, in addition to fitting of diameter and height, to improve tree taper estimation. Sprinz and others (1979) show that form class is relatively constant over a wide range of densities, but form class increases with age. The impact of change in tree form on volume estimation will be presented later.

Bower and Clason (1981) suggest the use of age in addition to tree diameter and height for estimating loblolly pine plantation component weights (stem wood, stem bark, branch wood, branch bark, and foliage). Relative tree component weights, of interest in defining hog fuel opportunities, are shown to vary by total age in loblolly pine plantations. For example, percent dry weight of stem wood ranged from 34 percent for 6-year-old trees to 77 percent for 30-year-old trees.

Key parameters for growth projection normally include age, stocking (trees per acre, basal area, or relative density [Reineke 1933]), competing species, and site quality.

Key variables in site quality estimation include site preparation treatments (cut with KG blade and pile, roll and chop, ripping, bedding, and others), soil series, topography, and climate. Several of these variables may be integrated through soil site equations to provide estimates of site index. A key to reliable dominant height projections is the development of representative site index curves through stem analysis and an objective procedure for site tree selection. Selection of a constant number of site trees per unit area, for different aged stands, appears to be more consistent for stem analysis-based site curves.

A final attribute for intensively managed plantations includes appropriate codes for genetic families. Growth projections can be modified for plantations based on gains exhibited from progeny tests.

Although these attributes can be included in a forest inventory, the choice depends on a forest manager's objectives and on incremental costs and values of obtaining the attributes. In the following section, I will discuss how some of these attributes affect volume or value estimation.

IMPACT OF STAND ATTRIBUTES ON VOLUME ESTIMATION

Errors or omissions in measuring an attribute affect estimation of (1) stand table, (2) stocking, (3) spatial distribution of stocking, (4) dominant height, (5) tree form, and (6) competing species.

Stand Table Estimation

Estimates of number of trees per acre by diameter classes provide information on product opportunities for thinnings or final harvest. Product opportunities include posts, poles, chip-n-saw logs, band saw logs, and plywood logs. In addition to these solid wood opportunities, additional products include fiber and hog fuel. Because product values rise with increasing tree size, higher stand values are calculated when a normal "bell-shaped" tree frequency distribution by d.b.h. classes is used than if all trees were assumed to be identical in size (equivalent to the average-sized tree). This is due to the linear relationship of value ($/cubic foot) with diameter and to the nonlinear relationship of tree volume with diameter. For data from two Louisiana loblolly pine plantation studies (aged 22 and 30 years) (Sprinz and others 1979), I estimated dollar value per acre to be 3 to 4 percent higher given the actual diameter frequency distribution, as compared to evaluating the "average-diameter tree," given the same volume per acre. Thus, stand average models could underestimate value by not taking into account the frequency distribution of diameters.

Stocking

A recent cruise of 24 young (6-year-old) loblolly plantations indicated a coefficient of variation (cv) (between 1/40th-acre plots) for stocking of 39 percent and for dominant height of 15 percent. Given a cv for stocking and an allowable error, sample size could be calculated. What value should be used for allowable error? Table 1 shows how errors in stocking determination at age 10 are expected to translate into errors in volume at age 10, 20, 30, and 40 years. According to yield tables by Hafley and others (1982), the impact of errors in stocking on volume estimates becomes less as the projection period increases. This is because low-density loblolly plantations eventually catch up in volume with high-density plantations. This relationship is also demonstrated by a long-term spacing study at Homer, LA (Sprinz and others 1979).

If allowable error is set at 20 percent for stocking at age 10, volume should be estimated at age 10 with slightly higher accuracy (table 1.), but projected volume to age 40 should be within ±2 percent. Projected average diameter varies somewhat more than volume, about ±5 percent.

Table 1.--Effects of sampling errors in stocking on estimated[1] volume yield by age, for site index 50, loblolly pine plantation

Age	Error in estimated volume: Ft³/acre	Percent
A. Underestimate stocking at age 10 by 122 trees/acre (455 vs 577), -21 percent		
10	- 59	-15
20	-219	-13
30	-205	- 7
40	- 49	- 2
B. Overestimate stocking at age 10 by 176 trees/acre (753 vs 577), +30 percent		
10	+ 69	+18
20	+225	+13
30	+211	+ 8
40	+ 38	+ 1

[1]Volume predictions from Hafley and others (1982).

Spatial Distribution of Stocking

Variation in stocking (stems per acre) was determined from five young loblolly pine plantations in Arkansas. Plots were grouped into stocking classes to match the age 10 stocking classes provided in published yield tables (Hafley and others 1982). Volume per acre was estimated at age 10 and at age 40 for each stocking class (table 2).

Table 2.--Estimated[1] volume at age 10 and at age 40 by stocking levels at age 10--loblolly pine plantation

Stocking age 10	Percent of plots	Volume Age 10	Volume Age 40
Stems/acre	Percent	---Ft³/acre---	
255	34	369	3,764
368	34	490	4,018
575	26	668	4,050
749	4	778	3,896
1,013	2	889	3,501
Estimated volume for average stocking:		528	4,024
Estimated volume weighted by stocking:		515	3,925
Percent difference:		2.5	2.5

[1]Volume predictions from Hafley and others (1982).

A weighted average volume was obtained for all classes. Volumes were also estimated for "average" stocking and were only 2.5 percent higher than corresponding volumes weighted by stems per acre. The weighting procedure is more accurate, but differences are not large.

Dominant Height

The effects of relative errors in stocking on projected volume tend to diminish with time, as do effects of relative errors in dominant height. The magnitude of impact on volume, however, is greater for relative errors in dominant height (table 3). Even with long-term volume predictions (30 years), height errors continue to lead to substantial volume errors.

Table 3.--Effects of sampling errors in dominant height on estimated[1] volume yield by age, for 8- by 8-ft spacing, loblolly pine plantation

Age	Error in estimated volume	
	Ft^3/acre	Percent
10	+284	+74
20	+860	+50
30	+980	+36
40	+899	+29

[1]Volume predictions from Hafley and others (1982).

Tree Form

Table 4 shows how form class, form factor, and the "b" coefficient of volume on D^2H equations tend to increase with age.

Table 4.--Summary of age, form class, form factor, and "b" coefficient of volume on D^2H model for several loblolly pine plantation data sources

Data source	Total age	Form[1] class	Form[2] factor	"b"[3] coeff.
Smalley & Bower (1968)	10-31		0.367	0.0020
Sprinz & others (1979)	22	70	.376	.0020
Sprinz & others (1979)	30	76	.378	.0021
Hope, AR (unpublished)	41	81	.416	.0023

[1]Form class = Diameter inside bark at 16 ft./ diameter outside bark at 4.5 ft.
[2]Form factor = Volume tree/volume cylinder,with same d.b.h., total height.
[3]Model: Vol = b X d.b.h.^{2} X Tot. Ht.

While this small sample confounds geography and age, other data sets support the trend of increasing form with increasing age. The volume estimation system should be sensitive to changes in tree form with age.

Competing Species

Clason (1978) showed that removal of hardwoods from a 7-year-old loblolly pine plantation led to a 45 percent volume growth increase by age 12. Bower and Ferguson (1968) showed that increased shortleaf pine basal-area growth rates (+31 percent) also occurred from understory hardwood removal and that when only part of the understory was removed, starting with the larger hardwood stems, the overstory's growth response was proportionately less. These results indicate that inventory data for competing species may substantially improve growth forecasts for the primary species.

CONCLUSIONS

Among various inventory attributes for volume projection, dominant height is probably the most important. For loblolly pine plantations, the number of trees per unit area has a large impact on volume at time of assessment but has much less impact on long-term volume projections. An associated error occurs when trees per unit area are estimated on average d.b.h., which will influence value estimation. Competing species may have substantial impact on short-term volume projections. Stocking variability within plantations appears to have small impact in volume assessment. Variation in diameter, as expressed by the estimated stand table, can have important effects on tree value and on product opportunities. Finally, improvements in tree form with age should be quantified with the volume or taper system used, or else additional measurements should be taken to quantify form changes. These results are based on a sample of loblolly pine plantations and may differ somewhat with geographic variation in loblolly pine and with other species.

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245 STEM ANALYSIS: A CONVENTIONAL APPROACH TO VOLUME DETERMINATION

J. E. Brickell

ABSTRACT: This paper discusses the bias in calculated volumes of felled and dissected trees which is due to the customary assumption of paraboloid tree bole shape. It examines the relationship of bias magnitude to measurement interval and presents guidelines for meeting accuracy requirements. A study of volume determination methods reveals that although several mensuration techniques are effective, if stem measurements are closely enough spaced, Smalian's formula is most often used because it uses the simple geometric solid that most closely represents most of the tree and is easy to use.

INTRODUCTION

Although the title of this paper is "Stem Analysis: A Conventional Approach to Volume Determination," stem analysis involves a lot more than volume measurement. It includes measurement of a tree's diameter and height growth at various points in time; however, this paper concerns only volume determination from measurements on felled trees. Measurements can be taken on standing trees, if one wants to climb or use a dendrometer. Felled trees are easier to measure, however, because one then can use a diameter tape or calipers, or buck the tree into stem segments and measure cross-sectional dimensions with a ruler or tape. Bark thickness and any desired growth information can be taken, and internal defect can be measured. Precision of measurement is greater on felled trees, and mistakes are less likely.

BACKGROUND

A tree stem is a complex geometric solid--so complex that to describe it perfectly with a mathematical expression is impossible. Even if it were possible, each tree would require a different expression. Fortunately, we don't have to describe a tree or log perfectly--close is good enough. We can get close enough by adopting a simple geometric model to represent the tree stem or segments of the stem and estimating model parameters from measurements taken on the tree. Accuracy in determining stem volume of a felled tree depends upon two things:

1. The nature of the mathematical model used to represent the stem or stem segments.
2. The kind and number of measurements taken on the tree.

A good model requires fewer measurements to attain a given level of accuracy than does a poor model. On the other hand, if the right kind of measurements are taken, spaced closely enough on the tree, almost any model will give adequate results providing it exhibits a circular or elliptical cross-section. Such models would include the cylinder, paraboloid, cone, and neiloid. Since I'm slinging these terms around it might be a good idea to describe them.

Cone: Everyone knows what a cone is. It's a geometric solid in which diameter decreases at a constant rate relative to length as length is increased toward the apex.

Paraboloid: A geometric solid in which diameter decreases at an increasing rate relative to length as length is increased toward the apex. The square of diameter decreases at a constant rate.

Neiloid: A geometric solid in which diameter decreases at a decreasing rate relative to length as length is increased toward the apex.

Frustrum is just a Latin word meaning "piece cut off" which has been adapted in mathematics to describe a segment taken from a geometric solid.

According to Fernow (1907), a German forester named Oettelt first used a mathematical model for a tree stem in 1765. He used a conic model. After looking at *Pinus ponderosa* var. *scopulorum* in extreme eastern Montana, I can see how his model could have been accurate. For most trees, though, modeling the tree stem as a series of paraboloid frustra seems more accurate, and this approach generally has been accepted as standard since about 1820. It has been long recognized, though, that the top portion of the bole more closely resembles a cone than a paraboloid, so the usual practice has been to model the top portion of the stem as a cone and the rest as a series of paraboloid frustra. Some people have recognized that the butt portion of the tree more closely resembles a neiloid than a paraboloid; however, Bruce (1970) used a solid model composed of a quasiconic frustrum surmounted by a cylinder to approximate the shape of Douglas-fir (*Pseudotsuga menziesii*) butt logs.

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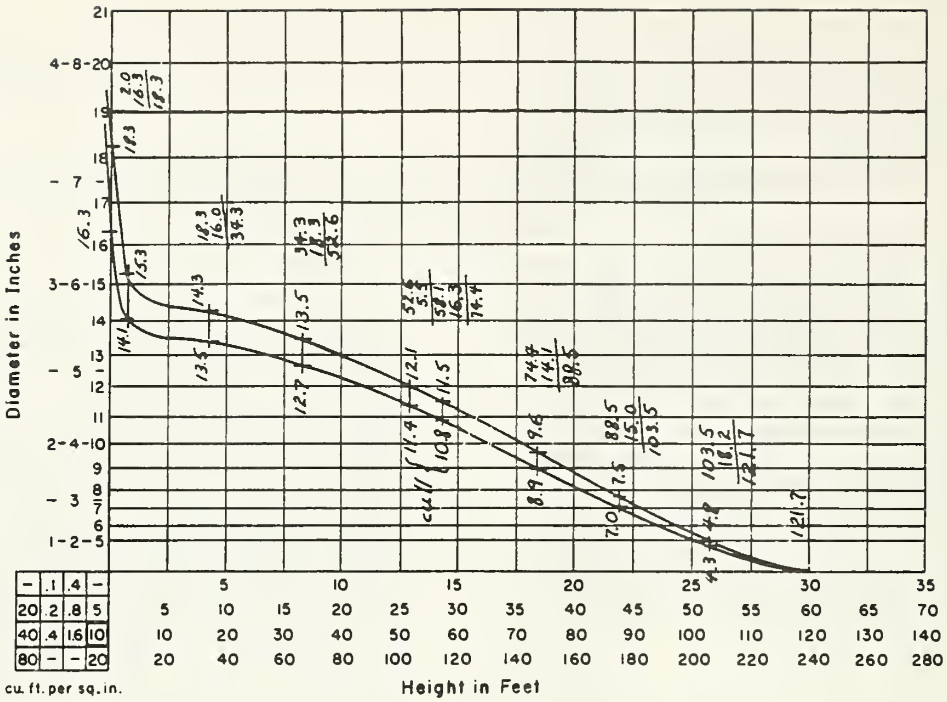

Figure 1.--A plotted tree system profile on USFS form 558a.

Reineke (1926) devised an approach to volume determination which was ingenious in its simplicity and involved no explicit assumption at all about stem form models. He used a piece of graph paper called form 558a on which the vertical axis was scaled in terms of squared diameter. The horizontal axis was tree length. One had only to plot his stem measurements on form 558a, sketch in a curve to connect them, and measure the area under the curve with a planimeter. A simple multiplication could then convert graph area to tree volume. An example of a plotted stem profile is shown in figure 1.

With this approach, the only assumption relevant to a geometric model resulted from the way in which the taper curve was sketched. For example, most people think that tree diameters get smaller toward the tip. If a measurement seemed to suggest the contrary, the sketcher might ignore it and make his curve taper toward the tip anyway.

Since Reineke's time a number of people have chosen not to sketch the taper curve by hand but to fit a mathematical function to the measurements. Cubic volume of the tree bole between any two points is obtained by integrating the taper function between those points. This amounts to just evaluating a function if the taper curve is integrable in closed form. Fitting a taper curve requires some assumptions as to proper curve shape, but they need not be as restrictive as the adoption of a specific geometric solid for a model. Use of taper curves requires more statistical skill than is possessed by most foresters, and until computers were available in the early 1960's, the burden of calculation made fitting taper curves impractical.

Despite the superior accuracy of taper curves, properly used, for volume determination, many people still use the paraboloid frustrum model for most of the tree stem. They use Smalian's formula, and the paraboloid shape is implicit in that formula. Many people know that Huber's formula also assumes a paraboloid shape and that it is superior in use to Smalian's. Why, then, is it not more commonly used? Because it requires a diameter measurement at the center of the stem segment, and, if measurements are not taken at just the right intervals, it is impossible to position them at the center of a stem segment without leaving some of the tree bole unaccounted for. This is illustrated in figure 2. So Smalian's formula it is, for better or worse. The trouble is that because of the paraboloid shape assumption, Smalian's formula tends to overestimate volume. How much this positive bias amounts to depends upon actual shape of the tree bole and the frequency with which measurements are taken.

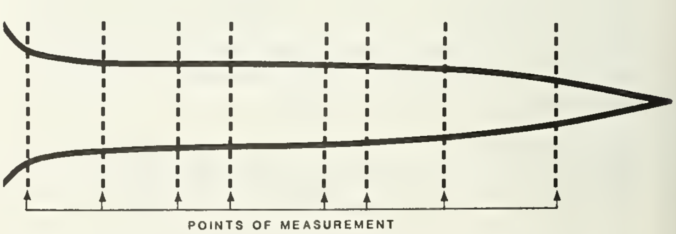

Figure 2.--A situation where Huber's formula can't be used.

Table 1.--Total cubic-foot volume differences: four formulas[1] compared with Newton's formula; differences expressed as a percentage of volume computed by Newton's formula (Dilworth 1961)

Log group	Formula			
	Huber's	Smalian's	Rapraeger's	Sorenson's
		STUDY I (DOUGLAS-FIR)		
Butt	-4.9	+ 9.9	- 0.1	- 4.5
Intermediate	-0.8	- 1.6	- 6.2	-10.6
Top	+0.6	- 1.4	-16.3	-22.1
Weighted average	-2.9	+ 5.8	- 4.7	-13.8
		STUDY II (WESTERN HEMLOCK)		
Butt	-5.6	+11.2	+ 0.5	- 2.7
Intermediate	+0.5	- 1.0	+ 0.3	- 3.7
Top	-2.1	+ 4.4	-23.0	-28.6
Weighted average	-2.2	+ 4.4	- 1.4	- 5.2

[1]Huber's formula: $V = \frac{\pi}{4 \cdot 144} D_m^2 L$

Smalian's formula: $V = \frac{\pi}{4 \cdot 144} \frac{(D_\ell^2 + D_s^2)}{2} L$

Rapraeger's formula: $V = \frac{\pi}{4 \cdot 144} (D_s + \frac{L}{16})^2 L$

Sorenson's formula: $V = \frac{\pi}{4 \cdot 144} (D_s + \frac{L}{20})^2 L$

Newton's formula: $V = \frac{\pi}{4 \cdot 144} \frac{(D_\ell^2 + 4D_m^2 + D_s^2)}{6} L$

where

D_s = diameter at the small end of the stem section

D_ℓ = diameter at the large end of the stem section

D_m = diameter at the middle of the stem section

L = section length

V = cubic volume

Smalian's formula gives reasonably accurate results for segments in the middle portion of the bole but usually grossly overestimates volume in the butt portion. Dilworth (1961) showed the magnitude of errors that can be expected from Huber's, Smalian's, Rapraeger's, and Sorenson's formulas. His information is summarized in table 1.

Barnes (1945) reported that Smalian's formula overestimated cubic volume in butt logs of western hemlock by 10.8 percent. Most forest mensuration texts recognize that a truncated paraboloid is not a satisfactory model for the lower portion of a tree stem, and usually suggest a neiloid. Bruce (1970), however, has shown that a neiloid is also inadequate. He had good results with an equation that corresponds to a composite solid comprised of a cylinder with the diameter of the small end and a concave solid of revolution resembling a truncated conoid.

Spaeth and others (1952) indicated that overestimates from Smalian's formula may not always be confined to the butt section of trees. In their experiment, Smalian's formula gave volume estimates for fenceposts 7-ft long that averaged 6 percent larger than volumes measured by displacement of water in a tank.

Grosenbaugh (1966) emphasized that trees are not simple geometric solids; therefore, some error must be expected from formulas based on simple models. He suggested that such error can be kept within acceptable limits by keeping measurement intervals on the stem short enough so that diameter at the small end of a stem section is more than 0.8 the diameter at the large end.

Table 2.--A comparison of tree volumes computed by Smalian's formula with volumes measured by water displacement (Young and others 1967)

Species	Computed volume as a fraction of water displacement volume		Ratio
	8-ft sections	16-ft sections	
Spruce	0.997	1.035	1.038
Fir	1.032	1.096	1.061
Hemlock	1.035	1.102	1.065
White pine	1.003	1.042	1.039
Cedar	1.072	1.234	1.151

Young (1967) and Young and others (1967) reported results of an experiment in which volumes of felled trees were calculated with Smalian's formula using stem measurements spaced 8 and 16 ft apart. Volumes regarded as correct were measured by immersing tree pieces in a tank and measuring the amount of water displaced. Table 2 summarizes their results. Spacing measurements 16 ft apart led to volume measurements that ranged from 3.8 to 15 percent greater than those obtained by a measurement spacing of 8 ft.

Integrating a taper curve really assumes a cylindrical stem segment shape, yet if the taper curve is accurate, that procedure will yield the best estimate of tree volume short of water displacement. The reason is that the stem segments assumed in the integration process are of infinitesimal length.

Clearly, a number of different formulas will work if stem measurements are closely enough spaced. Smalian's is most often used because it combines the paraboloid--the simple geometric solid that most closely represents most of the tree--with simplicity and ease of use.

So how closely should measurements be spaced to achieve any given level of accuracy if we are to use Smalian's formula? Is there any general rule that can be followed?

A QUICK AND DIRTY INVESTIGATION

To investigate this question I conducted an experiment in stem measurement by computer simulation. I selected the most accurate taper curve that I could find in the literature, which was the Max-Burkhart splined polynomial fitted to yellow poplar (*Liriodendron tulipifera* L.) (Martin 1981). This equation was most accurate both in precision of fit and in its inherent flexibility to fit different portions of a tree. Also, of the several hardwood species to which the equation was fitted, yellow poplar is most like a conifer in form.

Over a diameter breast height (d.b.h.) range of from 4 to 20 inches and a height range of from 20 to 130 ft (depending upon d.b.h.), I calculated tree volumes in two ways:

1. By dividing the tree into segments, calculating diameter outside bark at each end with the taper curve, and applying Smalian's formula.

2. By evaluating the integral of the taper curve between the lower and upper ends of the stem segments.

Segment volumes calculated by each method were accumulated to obtain two different total tree volumes. Stump volume was calculated in the same way by both methods, namely, as the volume of a cylinder 1-ft tall having the diameter predicted for the tree at 1 ft in height by the taper equation. This procedure is often followed when calculating felled tree volume. The integral of the taper curve between ground level and 1 ft may have given a rather larger volume, which when added into the tree's total volume would have tended to obscure the expected overestimate to be obtained with Smalian's formula. Volume below stump height is often not as important as that above the stump anyway. Also, under method 1 (Smalian's formula), the topmost segment of the stem was treated as a cone, following the procedure usually employed in determining volume of felled trees. Both segment volume and total tree volume were printed as well as stored in a computer system file for futher processing. Initially the comparison was made for segments of fixed length. Lengths were 1, 2, 4, 8, 12, and 16 ft. Then the comparison was made using segment lengths which were fixed proportions of total tree height. Proportions were 0.05, 0.10, 0.15, and 0.20.

RESULTS

The bias in total tree volumes calculated with Smalian's formula was positive in all cases. The magnitude of the bias was clearly related to tree length and stem segment length. The volume bias observations obtained in this way do not comprise a statistical sample; however, that did not stop me from fitting a regression equation to the data

in order to characterize and quantify the relationship. The equation is:

$$B = b_0 + b_1H + b_2L + b_3F + b_4F^2 + b_5H^2 + b_6H^{-\frac{1}{2}} + b_7L/H^2 + b_8L^2/H^3 + b_9L^{b_{10}}H^{b_{11}}$$

where

b_0 = -0.0419630

b_1 = 0.192412 x 10^{-3}

b_2 = -0.482282 x 10^{-2}

b_3 = 0.523567

b_4 = -3.90049

b_5 = 0.689265 x 10^{-6}

b_6 = 0.151162

b_7 = -6.43048

b_8 = 26.8953

b_9 = 0.845992

b_{10} = 1.97294

b_{11} = -1.60748

H = tree height in feet

L = stem segment length in feet

F = L/H, segment length as a fraction of tree height

R^2 = 0.97507

S_{yx} = 0.002803

The coefficient of multiple determination and standard error of residuals cannot be interpreted as they could if the data were observations on actual felled trees, but they do indicate goodness of fit. Notice that in this equation F = L/H, so that either F or L will determine the other for any particular tree height. Figure 3 shows bias associated with Smalian's formula plotted over tree height for several different spacings of measurement. Measurements spaced 1 or 2 ft apart yield little bias regardless of tree height. A measurement spacing of 4 ft gives a bias of 2 percent or less for all tree heights. Measurements spaced farther apart than 4 ft may result in an unacceptable overestimate, depending upon height of the tree and what the user considers to be acceptable. It is noticeable that the rate of slope change (second derivative of bias with respect to height) changes sign for the 4-, 8-, and 12-ft curves, as it does for the other curves in the region of height not on the graph. This can be attributed to two artifacts of the way in which volume calculations were carried out:

1. Stump volume was calculated in the same way under both Smalian's formula and taper curve methods. In shorter trees, stump volume is a greater proportion of total volume than in taller trees. A greater portion of the tree's volume being calculated identically by both methods tends to reduce the apparent bias of Smalian's formula for total tree volume in shorter trees.

2. With Smalian's formula method, volume of the stem's top segment is calculated with a conic model. This is much closer to the true shape, and the shape given by the taper curve, than is the paraboloid. In shorter trees the top segment contains a greater proportion of total volume than in taller trees. A greater portion of the tree's volume being computed with less bias tends to reduce the apparent bias of Smalian's formula for total tree volume in shorter trees. A longer interval between measurements accentuates this influence.

For the reasons given above, the central portion of the tree stem--the portion treated as a paraboloid--contains a smaller proportion of total volume in short trees.

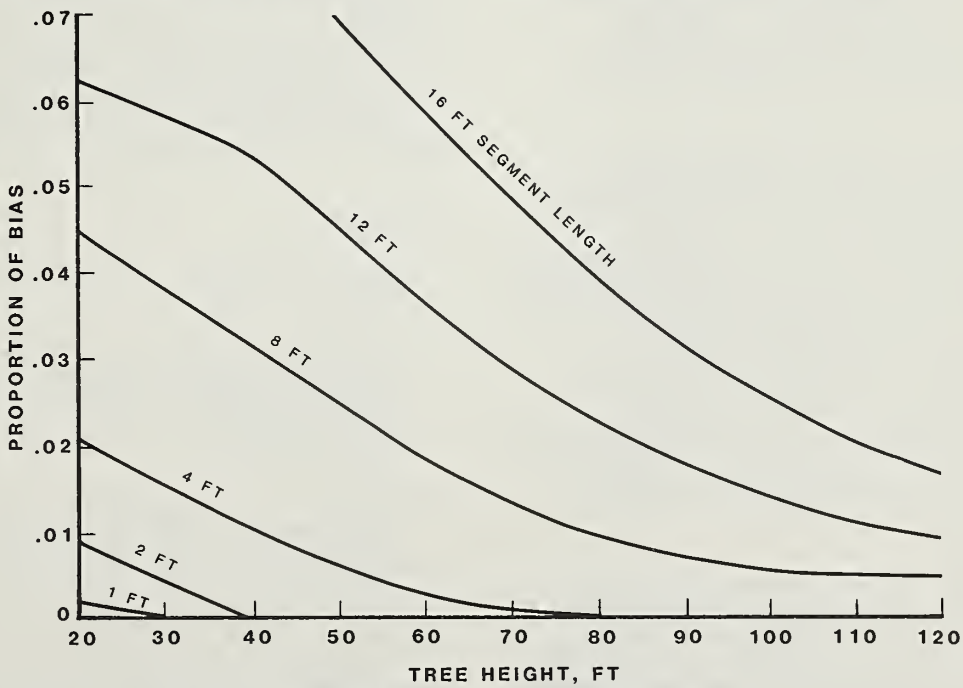

Figure 3.--The relationship between tree height, spacing between measurements, and bias of Smalian's formula.

Another feature of this chart can be noted: 4-ft measurement intervals for 40-ft trees, 8-ft intervals for 80-ft trees, and 12-ft intervals for 120-ft trees all give about the same amount of volume measurement bias. Evidently, for any given level of acceptable bias when using Smalian's formula, the appropriate spacing of measurements will depend upon height of the tree being measured. Recall the definitions of F and L in the bias regression equation. Figure 3 was created by evaluating the equation for fixed intervals of L and letting F be determined by L and H. (If the equation is evaluated for fixed intervals of F, figure 4 can be plotted.) Here again, for any particular segment proportion, shorter trees exhibit less bias than do taller trees, and this tendency is more marked for longer measurement intervals. The reasons are the same as for the reversal in sign of the rate of slope change in figure 3. An envelope curve is defined mathematically as a curve which is tangent to each of a family of curves. For this family of curves one can envision an envelope curve which is concave upward. The envelope curve defines, for each segment length proportion, a level of bias that will probably not be exceeded by using Smalian's formula regardless of tree height. For example, an interval between measurements which is 10 percent of the tree's height can be expected to give a 1 percent bias, or less. An interval of 15 percent will probably not give more than a 2.25 percent bias; a 20 percent interval, 4 percent or less, and so on. Apparently, if one wants the average bias of felled tree volume calculated with Smalian's formula to remain within some specified upper bound, this can be done at least cost by prescribing the interval between measurements on the stem as a certain proportion of stem length. With a little effort the regression equation could be solved for stem segment fraction given bias and height. The statistical problems involved in doing so wouldn't be a practical objection, but it seems just as easy to use a chart-like figure such as figure 4.

Specific numerical values given in this paper apply to yellow poplar in the Appalachians, for which the taper curve was fitted. The nature of the findings reported here will apply to all species with an excurrent bole. I could probably pass this off as an original piece of work--but I won't. Sixty years ago a German forester named Hohenadl reported the same results from an investigation on European tree species. He showed further that if one seeks a single key diameter to characterize a tree, then that diameter is more useful if it is measured at one-tenth the total tree height than if measured at breast height. Obviously, there are impracticalities in taking such a diameter, so we continue to use d.b.h.

Likewise, though the entire tree is accessible when it is felled, there may be impracticalities associated with using a fixed proportion of length as the measurement interval. For example, if we are stuck with board foot scaling diameters of 16-ft logs on felled trees, then the measurement interval will have to be 16-ft plus the trim allowance or some fraction thereof. Sixteen and a half feet might keep cubic volume bias within acceptable bounds for the largest trees, but for shorter trees 8.25-ft might have to be used. If the tree is quite short, an interval of 4.12-ft might even be advisable. Such a set of measurements might provide for reasonably accurate cubic volume calculation and still ensure the measurement of scaling diameters.

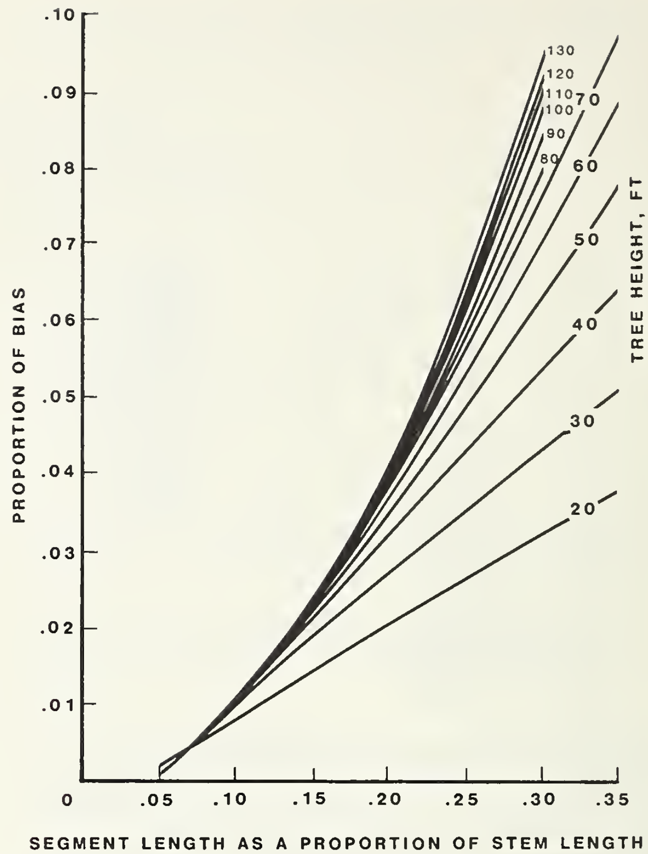

Figure 4.--The relationship between tree height, fraction of stem between measurements, and bias of Smalian's formula.

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VISUAL SEGMENTATION FOR WOODLAND TREE VOLUME MODELS IN THE ROCKY MOUNTAIN STATES

J. David Born

ABSTRACT: Tree volume models used to generate volume tables are generally not available for woodland species such as pinyon, juniper, and oak. The variable form of these species presents problems for conventional volume model development procedures. A visual segmentation procedure using data estimated ocularly from standing trees can be substituted for destructive sampling. In a test, data from the visual method compared favorably to felled tree data in constructing volume models. Procedures are described to collect data and include the data collection with forest inventory operations.

INTRODUCTION

In recent years the demand for fuelwood and other local products from pinyon (Pinus), juniper (Juniperus), oak (Quercus), mesquite (Prosopis), and other species characterizing woodlands in the Rocky Mountain States has increased dramatically. During the 19th century these species were heavily utilized for fuel and to support mining activities; however, as fossil fuels became more available and mining activity decreased after the turn of the century, vast areas were left to reforest. Increased grazing and control of wildfires undoubtedly helped sustain and increase the acreage of land supporting woodlands. Although during this century woodland species have been considered a deterrent to forage production for livestock and game, attempts to eradicate the trees have been costly and largely unsuccessful on a long-term basis.

Since 1928, when the McSweeney-McNary Act directed the U.S. Department of Agriculture to keep a current inventory of the Nation's forest resources, Forest Survey has made periodic assessments of forest resources. Only recently, however, has Forest Survey reported more than general area statistics for woodlands.

Previously, the focus was on information about timberland, that is, land growing species used for industrial wood products. With the passage of the Resources Planning Act of 1974 and the almost concurrent increase in demand for wood as an energy source, Forest Survey jumped into the woodland inventory business in the Rocky Mountain States.

Since 1974, when we tested our first woodland inventory procedure on the Carson National Forest in New Mexico (Born and Clendenen 1975), we have conducted extensive inventories in all of the Rocky Mountain States. Since the beginning that procedure has included subsampling for data needed to construct volume tables. We call the procedure visual segmentation. The volume equations and tables for the Carson inventory have been published (Clendenen 1979).

Tree volume models, or volume tables, have generally not been available for most woodland species. The extremely variable form caused by species differences and treatment history precludes the use of general models over large areas. Of course, the high cost of destructive sampling alone is motivation for a search for alternative techniques.

SUBSAMPLING

We use fixed-area circular plots which are usually spaced on a sampling grid to sample woodlands. Plot sizes range from 1/20 acre to 1/5 acre, but 1/10-acre plots are the most common. A tree is measured for volume if the diameter near the base exceeds 3.0 inches.

The first tree tallied under 10 inches in diameter is selected for visual segmentation, as is the first tree over 10 inches. The next tree tallied over 18 inches is also selected, regardless of the size of the other two trees. This is done to strengthen the volume models for larger trees, which are not common on the plots. The usual measurements are made on the trees selected for visual segmentation. These measurements are those common to most surveys with two exceptions:

1. DRC. The tree diameter is measured at the base or ground line, with some exceptions (fig. 1). DRC means diameter at root collar and, although sometimes a misnomer, it is used as an acronym for a basal diameter measurement.

When a tree is multistemmed at or near the base, an EDRC or "equivalent" DRC is recorded. The diameters for the stems are each squared and

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summed, and the square root of the sum is the diameter of a tree of "equivalent" basal area--a simple procedure with a pocket calculator. Trees requiring an EDRC measurement are common.

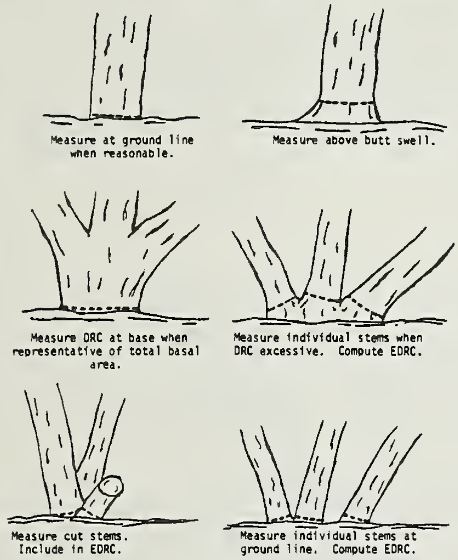

Figure 1.--Examples of DRC and EDRC measurements.

Trees with 3.0 inches or larger DRC or EDRC are measured for volume. A multistemmed tree needs only one stem this large, and any stem having a qualifying segment, regardless of diameter, is included in the EDRC. A qualifying segment must be at least 1 foot long and be at least 1.5 inches in diameter at the small end.

2. Number of stems. The number of stems measured for DRC or EDRC is recorded. This variable is used in our volume models.

If you are interested in our inventory procedures, please refer to one of our recent field manuals (U.S. Department of Agriculture 1982).

VISUAL SEGMENTATION

Trees are visually segmented in a manner similar to measuring felled trees for volume. Lengths and diameters are recorded for segments in each stem and branch in the tree. Remember, we measure any part of the tree that has qualifying segments, so both branches and stems are included to a 1.5-inch minimum diameter (outside bark). Figure 2 shows a tally form with two example

WOODLAND TREE SEGMENTATION RECORD

State/County 0 8 / 0 3 7 (1 2 3 4 5) NFS Region/ BIA Area/ BLM Resource Area 0 (6) Forest/ Agency/ District 9 9 (7 8) Subunit/ Reservation/ Planning Unit 0 5 (9 10)

Location No. 0 1 2 3 (11 12 13 14) Owner 7 0 (15 16) Sample Area 0 3 (17 18) Date 6-25-85 Crew D. Recorder, C. Cruiser

Pt. No. 0 3 Tree No. 0 1 Species 1 3 3 DRC 1 2 5 No. Stems 0 1

Total Ht. 1 6 No. Segments 0 1 4 Radial Growth 0 6 Estimator 0 1

Record Multiple Stems DRC Below

1 - Foot Length Class		2	4	6	8	10	12	14	16					T
SUMMARY	1													
	2	3		1	1									5
	3			1										1
	4	2	5			1								8
	5													
	6													
TOTAL		5	5	2	1	1								14
DOT COUNT		2	4	6	8	10	12	14	16					T
	1													
	2													5
	3													1
	4													8
	5													
	6													

Pt. No. 0 4 Tree No. 0 7 Species 0 6 5 DRC 3 4 4 No. Stems 0 4

Total Ht. 3 2 No. Segments 1 0 9 Radial Growth 0 4 Estimator 0 1

Record Multiple Stems DRC Below

13.6	14.7	16.5	22.6		

1 - Foot Length Class		2	4	6	8	10	12	14	16	20				T
SUMMARY	1	12	2											14
	2	16	12	14	1		1		1					45
	3	3	12	1	6									22
	4	2	4	3	3	2	2							16
	5			3		4	2	1						10
	6				1					1				2
TOTAL		33	30	21	11	6	5	1	1	1				109
DOT COUNT		2	4	6	8	10	12	14	16					T
	1													14
	2													45
	3													22
	4													16
	5													10
	6													2

Figure 2.--An example of segmentation recording form.

trees recorded. The first heading includes information about the plot, and the heading inside the box describes the tree. Multiple-stem DRC's are individually recorded in the boxes shown.

Segments are tallied by 2-inch diameter classes and 1-foot length classes using a dot tally. Figure 3 shows the preferred sequence for tallying segments in a tree to avoid missing branches and stems or even double tallying a portion of the tree. We have found that methodical application of the procedure is very important in assuring quality data.

Figure 3.--The order of segment tallies.

Most woodland trees are not very tall, but it is still difficult to estimate diameters and lengths in the upper part of a tree. To assist with this task we have adapted measurement poles developed at the Southeastern Forest Experiment Station (McClure 1968) to our needs. These 5-foot segment poles have both diameter and length reference markings, and they can be connected together as needed to reach the upper part of the tree.

Segment diameters near the base of a tree should be measured, especially if the stems are large. One cooperator asked his crews to climb the trees and make the measurements--quality data for sure!

DATA ANALYSIS

Procedure Verification

When most of the measurements used to compute tree volumes are visual estimates, one might reasonably question the reliability of the results. To determine reliability we conducted a study in Nevada to test the visual procedure against felled tree data. The results of this study are reported in Born and Chojnacky (1985). This publication also documents the current visual segmentation field procedure and contains complete field instructions and a tally form.

Figures 4 and 5 briefly indicate the results of the verification study. The regression lines developed from visual data tend to follow the felled tree data line closely except for larger trees. Here, for juniper, the direction of the difference depended upon the estimator. For pinyon all of the estimators underestimated the actual tree volumes for larger trees.

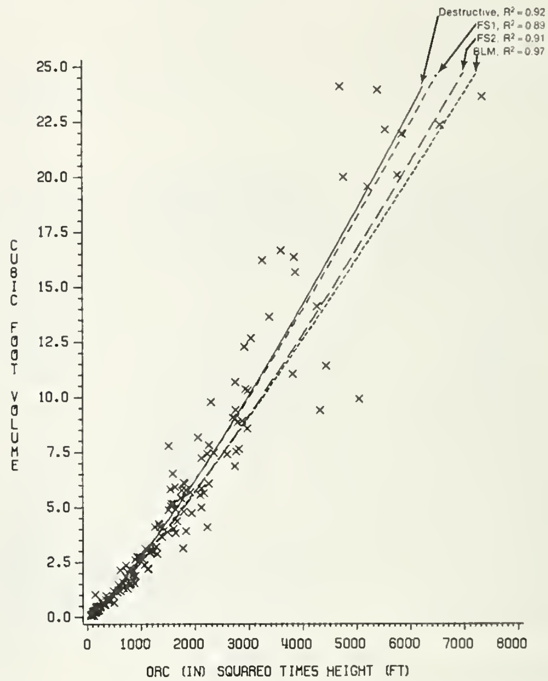

Figure 4.--Pinyon destructive segmentation data in cubic feet with a regression curve (solid line) and three curves for visual estimates overlaid.

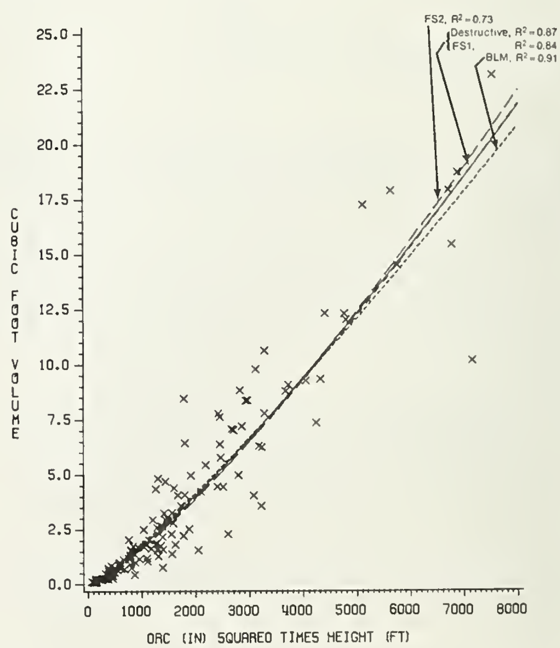

Figure 5.--Juniper destructive segmentation data in cubic feet with a regression curve (solid line) and three curves for visual estimates overlaid.

We believe that the underestimates for larger trees can be remedied by improved training and diligent use of the segment poles. Coincidentally, the three estimator groups ranked proportionate to their training and experience.

As expected, the visual method results in more variability in the data; however, this does not present any problems for the regression modeling if the procedure is carefully applied to avoid bias. More recent data we have collected tend to support these conclusions.

Volume Models

The segment volumes are computed by class and summed to obtain the total tree volume. Each segment is assumed to be a paraboloid frustum, and Huber's formula (Husch and others 1982) is used to compute the volume. This formula uses only the length and midpoint diameter.

The volumes are gross volume and include dead material that is usable for fuelwood. When volume has been cut from sample trees, we reconstruct the missing material or take the next appropriate tally tree, so that our volume models express total gross volume.

The tree volumes are used to develop a regression model using DRC, total height, and number of stems as predictor variables. Other variables are available, such as crown size and volume, but they add little that accounts for model variation. We have almost standardized our woodland tree volume models using the following form:

$$V = [a + b(DRSQH)^{1/3} + c \cdot STEM]^3$$

where: V = gross tree volume

DRSQH = DRC (inches) squared times height (ft)

STEM = 1 for single stem tree, 2 for multiple stem tree

The volume equation coefficients for woodland species in five States are included in Chojnacky (1985).

These equations were not intended for use in determining the volume of individual trees, so they should be used with caution. We believe the equations can be used effectively for inventories and cruises in the areas in which they were developed.

The volumes computed from the equations include all stem and branch volume to a 1.5-inch minimum diameter. We consider this minimum diameter to represent maximum practical utilization for fuelwood; however, I am sure that all of you have seen fuelwood cutting areas where the average minimum diameter was larger than this.

We have developed adjustment factors to apply to our equations to reduce the volumes for minimum diameters up to 6 inches (Chojnacky in preparation). The factors are simply ratios to multiply by the total tree volumes from the equations to obtain the utilizable volume at the new standard.

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BRIEF HISTORY AND DISCUSSION OF BIOMASS ESTIMATION FOR TIMBER TREE SPECIES

Eugene M. Carpenter

ABSTRACT: This paper gives an overview of the history, modeling techniques, availability, and application of equations and methods to estimate timber tree biomass in the United States.

INTRODUCTION

The purpose of this paper is to introduce biomass estimation to field foresters and others not familiar with these estimation techniques, to show sources of biomass information, and to briefly discuss biomass modeling methods and their application.

HISTORY OF BIOMASS ESTIMATION

A French forester, J. Pardé, published a review article in Forest Products Abstracts in August 1980 entitled "Forest Biomass." He outlined the development of studies on the biomass of trees and forest stands throughout the world and contended that, although forestry schools have existed for 150 years, only recently have researchers addressed the question of woody biomass. Between 1950 and 1979 many works on mensuration and production appeared. But up to 1974 most dealt only with the volume of forest trees. Interest in the weight of trees stemmed from the conjunction of three factors:

1. Weight scaling, especially by fiber-oriented industry, which began in the early 1960's but which was limited to the merchantable bole component.

2. Scientific "fundamentalists'" concern for documenting the biologic productivity of forest ecosystems, which also increased markedly in the 1960's.

3. The 1973 oil crisis and the attention focused on the utilization of wood as a renewable natural resource for both energy and chemicals.

The latter two especially could be analyzed most readily in terms of the dry weight of plant material.

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To these factors we might add:

4. The development of whole-tree chippers and the need to determine whole-tree weight to convert inventory and harvest to a tons-per-acre basis.

5. New product development capable of using a greater portion of a tree.

6. The concurrent interest in nutrient capital cycling to determine what is removed when whole trees are harvested from the site.

It is not surprising that foresters were interested only in the volume of wood in boles and, at best, large branches. This interest was totally driven by the raw materials wanted for industrial processes and the economics of harvesting. Merchantable volume to a limited top diameter, such as 9 inches or 4 inches, could be calculated by accepted standard formulas, such as Huber's, Newton's or Smalian's, by stem analysis, taper functions, or a variety of log rules, such as International, Doyle, Decimal C, and the like. Bole volume was satisfactorily expressed in board feet, cords, or cubic feet.

The first idea for estimating the weight of stems was to start with wood cubic foot volume and convert to weight by multiplying the volume by density (mass per unit volume) using constant moisture content. This was not without problems because density and specific gravity can fluctuate with geographic location (provenance), position in the tree, the proportion of early and late wood (which can be influenced by climatic variation), and site, especially altitude. Studies documenting density and specific gravity became very important, a good example of which is Stage's (1963) work with lodgepole pine.

Subsequently, the problem became one of estimating tree or product weight directly from such measured tree variables as diameter and height. Pardé (1980) points this out as a classic problem in forestry: volume (weight) tables are required for each tree species. Thus, for a species, a sample of trees representative of the species population is selected, felled, and subsampled to obtain fresh and dry tree weights. These weights are then related to the measured tree variables by some mathematical model. In some studies the stem sections, limbs, and foliage are weighed in the field. Other studies weigh limbs and foliage, calculate stem volume from interval measurements of diameter using taper functions or Smalian's

formula, and determine green and dry weights of stems from weighted average tree density and moisture content.

BIOMASS MODELING

A tremendous amount of research has addressed selecting the best mathematical models to fit sample data. The process is rigidly technical. For most models the independent variables used are diameter breast high (d.b.h.) or a combination of d.b.h. and height. Most researchers have found other measures, such as crown ratio, form class, age, site index, or stand basal area, add little to the accuracy of single-tree prediction, and some are difficult to obtain. An exception might be the prediction of crown, branch, or foliage weights where diameter at the crown base or crown length adds significantly to the accuracy of estimating these components.

D.b.h. alone is good for estimating biomass in an even-aged stand. But height, which is influenced by site, age, and diameter, is important in developing so-called generalized equations. These are equations developed where trees from many different site conditions are represented in a study.

Schlaegel (1982) provides a particularly good discussion of model selection and use. He reports it may be necessary to evaluate four basic models before making a choice for best fit. These are: the simple linear, the transformed allometric, the weighted linear, and nonlinear models. The biggest problem with the simple linear model is that the assumed condition of equal variance is often not satisfied if the range of the independent variable (usually d.b.h. or d.b.h. and height) is large. The problem of heterogeneous variance can be satisfied by using a weighted linear model in which the weighting may give a satisfactory minimum variance. An explanation of the procedures is given by Freese (1964).

The allometric model is probably the most widely used for biomass estimation. Although nonlinear, it can be fitted by least squares techniques through logarithmic transformation. This, however, presents the problem of interposing a bias into the process when the logarithmic predictions are converted back into arithmetic units. Crown weight is underestimated by 5 to 10 percent and bole weight by <1 to 2 percent. Baskerville (1972) has provided a method to correct for this bias and Beauchamp and others (1973a) have extended the work and have developed a computer program to compute unbiased allometric regression estimates (Beauchamp and others 1973b). Other nonlinear models can be fitted, but they take great skill in biometrics. Payandeh's (1981, 1983) papers provide excellent discussions of these problems.

Accuracy of most prediction equations varies by component. Usually those for the bole and total aboveground biomass are most accurate, having high coefficients of determination and low standard errors. The equations fit the data well and individual observations vary little from the mean. Live-crown predictions are often intermediate in accuracy, while dead-branch prediction is at best a good guess. Precision for these latter components can be increased when equations include an upper-bole measurement as one of the prediction parameters, such as diameter at one-third the height. Also, this may be a way to extend the use of an equation to locations beyond the area in which the sample trees were located. Many authors are now providing this capability.

Schlaegel's 1982 paper is particularly useful for the discussion of selection criteria to measure fit. He presents five statistics in addition to the commonly reported coefficient of determination (r^2) and the standard error of prediction ($S_{y.x}$) and shows how they can be used to compare models as well as choose the best one. An example is included in his paper on green ash volume and weight estimation (Schlaegel 1984). Also important is the development of confidence bounds for an estimate and the problems one faces in attempting to do this. Methods are available to calculate the confidence limit for each tree as well as the sum of any number of trees when simple or weighted linear models are used. But the author must provide the mean ($\bar{x}$) and the corrected sum of squares for the independent variable (x). In addition, approximation can be made for nonlinear models, but not all of the theory has been worked out for nonlinears.

STAND BIOMASS ESTIMATION

Perhaps the most important step is getting from the point of tree biomass to stand biomass. One way is to use the mean tree method, which requires an inventory to accurately determine the mean tree dimensions for the stand. For pure, even-aged stands the tree of mean basal area is best. Lacking a prediction equation to estimate weight, Pardé suggests 5 to 10 mean trees can be felled and weighed and the component mean biomass values determined. By multiplying these data for the mean trees by the total number of trees, the total stand biomass is obtained.

An alternative, when prediction equations are available, is to develop a stand table showing the number of trees by diameter class and total height and applying the prediction equation to obtain the results. A weight yield table, developed from the prediction equation, can be constructed for a variety of diameter and height classes or the equation can be solved for each tree in the stand or plot. For mixed stands, equations for each species are required.

Another method is to use stand basal area and the mean height of dominant and codominant trees as the prediction parameters (Faurot 1977; Schlaegel 1975; Alban and Laidly 1982).

Combining the work of several researchers to provide an estimate of total biomass may be a useful alternative. Hanley (1976) used this method in predicting biomass and productivity for grand

fir, western redcedar, and western hemlock habitats in northern Idaho. He used Stage's (1966) volume equation converted to weight by means of specific gravity for the stem wood estimate. Crown components were estimated from Brown's (1976) work in estimating forest fuels. For bark and roots it was necessary to consult regional work in progress by Faurot (1977) and Canadian data for some species--in all nine separate sources were used. By putting these all together Hanley arrived at an estimate of biomass. It may be possible, therefore, to make estimates to satisfy a particular tree component, species, or regional need if one is aware of the variety of sources of information.

Faurot's (1977) volume table work with ponderosa pine (Pinus ponderosa), lodgepole pine (Pinus contorta), western larch (Larix occidentalis), and Douglas-fir (Pseudotsuga menziesii) in developing volume prediction equations has a good methodology section and allows estimating volume to a variable top diameter. Schlaegel (1973, 1978, 1984) provides a ratio-estimation technique for predicting weight and volume to various selected top diameters.

AVAILABLE LITERATURE: BIBLIOGRAPHIES

Biomass bibliographic studies began with Keays' (1971a,b,c,d,e) work published in five parts corresponding to commonly used tree components: unmerchantable top of bole, foliage, branches, crown and slash, and stump-root system. Another bibliography, by Art and Marks (1971), primarily deals with dry weight biomass and annual primary production studies, and Madgwick (1976) provided a reference on the methodology of mensuration. One should consult Cunia's (1979a, 1979b) papers for a summary of a survey on statistical methodology. In the early to mid-1970's Harold Young acted as a caretaker of biomass literature in his connection with the IUFRO working party on the mensuration of forest biomass. He tabulated studies by tree component (Young 1976), showing author, species, number of trees, units (whether metric or English), range of d.b.h. and height of study trees, the independent variables used in the prediction equations, and whether fresh or dry weight was included. Subsequently, Stanek and State (1978) supplemented the list primarily with Canadian species. Finally, Hitchcock and McDonnell (1979) added 137 new equations to complement Young's and Stanek and State's work. In 1979, H. A. I. Madgwick's personal bibliography on the subject was reported by Pardé to contain more than 1,000 titles. Tritton and Hornbeck (1982) provide an excellent source of biomass estimation equations for the Northeast covering 24 tree species. Other recent bibliographic works include Howe (1978), Hann and Riitters (1982), Baldwin (1982), and Satoo and Madgwick (1982).

APPLICATION

Problems and Precautions

Before applying a biomass equation one should check the range of sample tree locations. Although there have been many timber tree biomass studies in recent years, the resulting equations often have limited applicability because sample trees were selected to represent local conditions.

Some of the earlier work in developing biomass prediction equations for several tree components resulted in biomass tables for the various components that were inconsistent among themselves. Jacobs and Cunia (1980) provide a method of using dummy variables to harmonize the function to allow similar shape and consistent spacing of the curves: when one tree component is part of a second tree component the regression estimates of the first must always be smaller than those of the second. Kozak (1970) also provides methods of ensuring additivity of biomass components by regression analysis. One should watch for the above inconsistency in using component equations. Jacobs and Monteith (1981), in a conditional evaluation of equations for nine tree species that compared weight estimates from studies in Maine, New York, and West Virginia, found great similarity among trees of the same species in these widely scattered areas. Three species had parallel and identical regression lines (equal slopes and intercepts); four exhibited parallel but not identical lines (equal slopes but statistically different intercepts). They suggest that regional weight tables are possible for some species.

Schlaegel (1975) found that volume estimates for aspen (Populus tremuloides) agreed so closely to composite tables applicable for a number of Lake States species that the dry weight for aspen boles could be extended to other species after correcting for specific gravity differences. If the average stand wood specific gravity of the sample trees is provided by the author, one can develop a correction ratio by sampling for specific gravity in the stand of interest.

An example of the development of generalized equations is Alban and Laidly's (1982) work with unthinned red and jack pine plantations in the Lake States. Twenty-nine jack pine and 28 red pine stands were selected to represent a broad range of age, site index, and basal area classes across the area. Regression coefficients or constants were developed to estimate nine tree components (foliage, live branches, dead branches, bole bark, bole wood, live crown, total crown, stems, and whole trees) using nonlinear equations with d.b.h. and total height as the prediction parameters. Alban and Laidly also developed estimates of stand component weight using stand basal area (B) and mean height of dominant and codominant trees (H). They used a simple linear equation ($Y = a + b\ (B)(H)$) to obtain predictions that compared closely to results from summing individual tree estimates for all trees on the test plots.

Nutrient Cycling

Much interest in biomass estimation relates to nutrient cycling or nutrient content. Van Lear and others (1984) point out the latter is particularly important because of the potential impact of intensive silvicultural practices such as short rotations, whole tree harvesting, and certain site preparation methods on the nutrient status and productivity of forest sites. They feel that using prediction equations to estimate biomass of tree components from tree diameter is preferable to using an average tree approach because the proportions of foliage, branches, bark, and wood change with tree size (Jokela and others 1981). In their study of loblolly pine plantations in South Carolina, Van Lear and others found crown biomass (limbs, foliage, and top above 5 inches) represented 20 percent of the above-stump biomass but contained 49 percent of the nitrogen, 45 percent of the phosphorus, 37 percent of the potassium, and 36 percent of the calcium. Also, to determine concentrations of nutrient elements in a stand it would be best to calculate stand component biomass from generalized prediction equations and determine nutrient levels by sampling in the stand of interest rather than using nutrient prediction equations directly. Nutrient concentrations in biomass may vary considerably from site to site while biomass equations are less site specific. The weighted nutrient concentrations determined from the sample multiplied by the predicted dry weights would then provide an estimate of the stand nutrient pool content.

FOREST SURVEY PROGRAM

A major national effort to estimate biomass was initiated in January 1980 with the formation of the National Tree Biomass Compilation Committee. This committee consisted of individuals from Resources Evaluation Projects in the North Central, Northeastern, Southeastern, Southern, Intermountain, and Pacific Northwest Stations and a representative from the Forest Products Laboratory in Madison. The first phase of their work was a national biomass compilation using state-of-the-art methods available to the individual research work units. This resulted in the publication "Tree Biomass" (USDA Forest Service 1981), which estimates the green weight of aboveground tree biomass on commercial forest land by a variety of regions, sections, species groups, and owner classes. The second phase was to identify research needs that surfaced in trying to assemble and apply available prediction equations and methods to accomplish phase 1. However, not much has happened as a result of this analysis. The third phase was to promote the integration of biomass estimation into the ongoing resources evaluation inventory system to make State-by-State analyses of biomass availability, and to assess the competition that might develop between fuel and fiber uses of biomass.

The effort in phase 1 was hampered by lack of information regarding the amount of wood and bark in the whole tree, particularly the crown, and the lack of specific equations for many tree species. In the Lake States, Rocky Mountain, and Pacific Coast regions, merchantable bole volume estimates from survey were converted to weight using available wood-density data. Then conversion factors were used to estimate bark, top, and limb weight as a ratio of bole weight. In the East and Alaska, tree-weight equations were available to apply to stand tables developed in the State-wide forest inventories enabling an individual-tree approach to estimate biomass.

In addition to the national report, regional reports were produced. An example is "Whole Tree Volume Estimates for the Rocky Mountain States" (Van Hooser and Chojnacky 1983). They present the wood-density and bark-to-wood ratios used to convert volume to weight and the equations to estimate bark, top, and branch weight. Although the regression parameters and constants developed provide somewhat imprecise estimates, they do provide a methodology to allow reasonable prediction of biomass on a State-wide basis. The authors point out that, by manipulating the tabulated data, several additional factors can be developed and used to divide existing resource estimates. For example, the biomass of tops and limbs from harvested trees can be estimated from timber removal data. Van Hooser and Chojnacky estimate that the percentage of total biomass in small trees, cull trees, and tops and limbs of growing stock trees is 34 percent of total biomass in the region.

These early regional reports are limited to material on commercial forest land. A further extension has been for Forest Inventory and Analysis (FIA) research projects to collect information to assess biomass on noncommercial and nonforest land, and to include shrubs and herbaceous vegetation--the whole ball of wax so to speak. An example is the multiresource inventories in the Southeast. Cost (1978) and Cost and McClure (1982) published papers detailing the methodology for developing State-wide biomass inventories. Of most interest may be the models developed to quantify the biomass of non-growing-stock trees as well as seedlings, shrubs, vines, grasses, and forbs--all important from the wildlife management standpoint and perhaps the nutrient pool analysis.

Cost and McClure developed four programs to process the data. The first converts merchantable volume to weight. The second tabulates number of trees, merchantable green weight, biomass green weight, and biomass component weight. The third converts cubic feet of space occupied by understory vegetation on commercial forest land to weight and shows per-acre weights for seedlings, shrubs, vines, grasses, and forbs. The fourth provides 13 biomass tables showing similar data for nonforest areas.

In March 1984, a Forest Land Inventory Workshop was held in Denver with the theme "Preparing for the 21st Century," intended, in part, to promote techniques exchange among Forest Service Regions and Stations as a means to improve the kind and

quality of inventory data (Lund 1984). Because FIA research projects now include an estimate of forest biomass in inventories, I expected to find how this was being done in the various Stations. Only the Southeastern Station highlighted their effort to measure timber tree biomass including stumps, limbs, and tops of trees 5.0 inches d.b.h. and larger. Intermountain explained their use of visual segmentation to estimate volume of "other species," primarily pinyon (Pinus edalis) and juniper (Juniper L.) and all other hardwoods except cottonwood (Populus L.) and aspen in woodland types. Most simply mentioned that an estimate of biomass was included in current assessments. The impression from reviewing the proceedings was that developing better biomass estimation methods was not a high-priority problem in most areas, even though somewhat crude methods are now used in the estimation process.

CONCLUSIONS

A major problem in estimating timber tree biomass is the lack of suitable equations for many species. There are very few generalized equations that can be used to cover an entire region, area, or species mix with which one might be working. As the Stations continue to include biomass as a part of State-wide forest surveys, I expect the voids for important timber species in the various regions will be filled through the development of additional prediction equations. Until then, however, piecemeal approaches will have to be used.

The potential to regionalize existing equations should be investigated. Several researchers have had encouraging results in comparing prediction equations for certain species from widely separated sample areas. Also, it may be possible to develop conversion factors or ratios to extend equations to similar species or other areas with a minimum of expense in destructive sampling and field weighing.

I have compiled a bibliography of publications on tree biomass prediction containing more than 325 entries. Copies may be obtained by writing to me.

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BIOMASS DETERMINATION OF NONTIMBER SPECIES OF PLANTS

Peter F. Ffolliott

ABSTRACT: With increasing demands for alternative energy sources, better means of determining quantities of biomass that are potentially available for energy use are needed. This need is especially apparent for nontimber species of plants, for which "standardized" mensurational techniques are incomplete and for which methods are more or less developed in response to local needs.

INTRODUCTION

Throughout the world, demands for biomass as an energy source are increasing. Many households, and even whole communities in the Third World, depend entirely on biomass, often derived from woody plant species, for cooking and heating (Boyce 1979). With these increasing demands, better methods of determining biomass quantities of woody plants that are potentially available for use are needed. In particular, this need is apparent for nontimber tree species and woody shrubs, for which mensurational techniques are frequently incomplete.

In many instances, there are no "standardized" mensurational techniques to determine biomass quantities of nontimber species of plants. Rather, methods are more or less developed in response to immediate needs in a particular locale. Because, however, nontimber tree species and woody shrubs are almost by definition of lesser value than commercial timber resources, it is not uncommon for only limited funding and time to be allocated to their assessment. Nevertheless, the determination of nontimber biomass can be a critically important mensurational undertaking.

Over the past several years, I have had several opportunities to work with mensurationists and inventory specialists in the United States and around the world in attempting to quantify the biomass of nontimber tree species and woody shrubs that might be available for subsequent energy use. Evolving from these opportunities has been a collection of "methodologies," some of which I would like to describe in this paper; for the most part, these are not innovative methods but applications of known approaches to meet specific needs.

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For purposes of discussion, I would like to define nontimber biomass as that derived from trees and woody shrubs having little value for primary wood products (for example, lumber, veneer, poles). Determination of biomass for timber species of commercial value has been discussed in a previous paper.

In this discussion of biomass determination for nontimber species of plants, three main topics will be mentioned: primary sampling designs, selection of trees and woody shrubs for measurement, and individual tree and woody shrub measurements. Major emphasis will be placed on individual tree and woody shrub measurements that are used to estimate biomass, however.

PRIMARY SAMPLING DESIGNS

Nearly any and almost all primary sampling designs can be or are used to measure nontimber biomass. Only rarely are complete enumerations of populations justified, but simple and stratified random sampling designs, and numerous combinations thereof, have all been employed at one time or another. In many Third World countries, where statistical integrity may be less rigid, systematic sampling designs are also used. Frequently, measurements of nontimber biomass are "piggy-backed" onto primary sampling designs that are utilized to inventory other natural resources, such as commercial timber, forage, or soil.

Occasionally, interpretations of aerial photography and ground measurements are coupled in various two-stage sampling designs to measure nontimber biomass. Again, many options exist, but the combinations that are chosen to select trees and woody shrubs for measurement must be consistent with stated goals of the biomass inventory.

In general, any design that meets the sampling objective can be used as the "vehicle" for obtaining measurements required to quantify nontimber biomass. Of course, the reliability of estimates drawn from the measurements of biomass largely depends upon the sampling procedure and intensity.

SELECTION OF TREES AND WOODY SHRUBS FOR MEASUREMENT

Nontimber tree species and woody shrubs can be selected for measurement through implementation of three general theories of sampling probability: probability of selection proportional to frequency, probability of selection proportional to size,

and, in a few cases, probability of selection proportional to prediction (3P). Most commonly, fixed-area plots or point sampling techniques are employed. Nontimber species of plants have been selected for measurement by 3P methods in a few instances, however.

INDIVIDUAL TREE AND WOODY SHRUB MEASUREMENTS

The individual tree and woody shrub measurements taken depend, in large part, upon the purpose of the nontimber biomass determination. In general, tree and woody shrub biomass can be quantified in terms of volume (cubic meters, cubic feet, cords); weight (kilograms, metric tons, pounds); or potential energy equivalents (kilojoules, Btu's, calories). Estimation of volume is frequently, however, the most difficult mensurational task.

Approaches that are considered in estimating the volume of nontimber tree species are presented below. Only rarely is the volume of woody shrubs estimated through plant measurements. To provide a reference point in this discussion, the unit of volume is cubic meters, although in principle, the remarks are independent of volume unit.

Individual Tree Measurements

In taking the measurements, two general tree forms, differentiated by types of branching, are often recognized: excurrent and deliquescent. In general, trees possessing a terminal leader, whose growth is prolonged to form an undivided main bole, are considered to be excurrent. Trees whose main bole is not so evident, but instead divides into a number of limbs, are said to be deliquescent. There are a number of variations within these general tree forms, however, so the following remarks should be broadly interpreted.

Excurrent Form

Trees characterized by an excurrent form are relatively easy to measure, as every forester worth his or her salt knows. One simply tallies by tree species (to identify the appropriate specific gravity value for determination of weight and potential energy equivalents), d.b.h., and for a subsample, height. When available, volume tables are then interpreted to obtain estimates of tree bolewood volumes. Unfortunately, volume tables are not always available to estimate the volume of nontimber species. In these instances, "rule of thumb" relationships, as presented below, are frequently employed:

$$\text{VOLUME (CUBIC METERS)} = \frac{\text{DBH (CENTIMETERS)}^2 \times \text{HEIGHT (METERS)}}{3} \times 10^{-4}$$

This equation is a "composite" expression of volume that has been derived from measurements of over 50 nontimber tree species in the United States and around the world. Testing to date suggests that solutions of the equation are reliable estimates of volume; however, it is important to remember that this equation is but a rule of thumb to be applied only in the absence of standard volume tables.

From the above, estimates of volume in tree bolewood are obtained. To expand these estimates to estimates of the total tree volume (including branches, twigs, and so on), various empirical relationships from the literature are extrapolated, whenever possible, to represent the conditions sampled. (A synthesis of the literature [Hitchcock and McDonnell 1979] suggests that softwood species have 15 to 20 percent of the total tree biomass in crown wood and leaves, whereas hardwood species have approximately 20 to 25 percent of the total tree biomass in crown wood and leaves.) Although these relationships may not directly apply to the particular nontimber tree species being measured, their use, in many cases, provides reasonable estimates of total volume of tree biomass from available inventory data.

Single-stemmed and multistemmed trees of excurrent form are measured as outlined above. When multistemmed trees branch at ground line or below d.b.h., the individual stems are considered to be single-stemmed. When, however, multistemmed trees branch above d.b.h., they are usually considered to be deliquescent in form, and individual tree measurements are taken accordingly.

Deliquescent Form

Trees that exhibit a deliquescent form are more difficult to measure and quantify than trees of excurrent form. When confronted with a deliquescent tree form, two questions arise almost immediately. What diameter and height measurements do we measure? How is volume estimated from these measurements? These questions cannot be easily answered. In attempting to do so, a forester often takes the liberty of discarding "traditional" measurements (such as d.b.h.) and replacing them with individual tree measurements; these are frequently based on destructive sampling and relate to the total volume of tree biomass.

Destructive sampling of nontimber tree species is conducted to define, if possible, predictive equations between the total volume of tree biomass and individual tree measurements that are easily obtained without bias. In my experience with studies of this kind (involving neem in the West Africa Sahel, the genus _Prosopis_ in the subcontinent of India, the genus _Acacia_ in the dry zones of Chile and Peru, and oak in the Southwestern United States), trees selected for destructive sampling are initially measured in a range of diameters, heights, and lengths, all of which can be incorporated into an inventory of nontimber biomass. The trees are then felled and cut into pieces of wood that in general correspond to local utilization practices. From these data, predictive equations are derived if statistically possible.

The results of the destructive sampling investigations cannot be generalized because the findings are too inconsistent. In some instances, statistically reliable predictive equations have been obtained to estimate the total volume of tree biomass. When this happens, the individual tree measurements specified are taken to directly solve the equations. In other cases, however, reliable predictive equations cannot be developed to any degree of accuracy. Instead, only "hints" as to the individual tree measurements that might "index" the total volume of tree biomass are discovered; for example:

1. Basal diameters (at ground line) can be a better predictor of volume than diameter measurements taken at breast height.
2. Total height measurements can serve as a predictor of volume, particularly in even-aged, human-made forests of uniform height.
3. The number of trees can also be used to predict volume, especially when this measurement is combined with diameter size and frequency distribution.

One final comment regarding the destructive sampling investigations is warranted. The preferred expression of tree biomass is frequently by weight and, ultimately, potential energy equivalents. When this is so, weighing the pieces of wood, rather than attempting to estimate volume and then converting to weight by multiplying volume by specific gravity values, may be the best approach.

From measurements of weight, potential energy equivalents are readily derived by multiplying weight by appropriate heat contents, the latter values being obtained from calorimetric measurements in the laboratory or the literature (table 1). Also, measurements of weight can often be related to individual tree measurements in predictive equations which, subsequently, are used to inventory tree biomass in terms of weight. This general approach can also be employed to measure the biomass of trees with excurrent form and, as discussed below, woody shrubs.

Table 1.--Heat of combustion values for selected nontimber tree species in the Southwestern United States (Voorhies and Huntsberger 1983)

Common name	Heat of combustion	Specific gravity
	Btu's/lb	
Arizona cypress	9,292	0.65
Arizona walnut	8,571	.59
Juniper, alligator	9,050	.45
one-seed	9,212	.57
Utah	9,394	.51
Mesquite	8,657	.70
Oak, Arizona white	8,038	.71
Emory	8,420	.64
Gambel	8,182	.63
Pinyon	8,913	.51

Individual Woody Shrub Measurements

The easiest and, perhaps, in general the most common, method of estimating the biomass of woody shrubs is through weight measurements. The complex forms of growth that inherently characterize woody shrubs preclude in most instances accurate estimates of volume. Therefore, through destructive sampling, weight is related to individual woody shrub measurements (height, crown form and relative size, foliated area). The resultant predictive equations are then used to convert inventory measurements of woody shrubs to weight, with later conversion to potential energy equivalents (as outlined above), if required.

FUTURE NEEDS

From my personal experiences in attempting to quantify nontimber biomass, various mensurational research needs can be recognized. Among the more important of these are:

1. Cost-efficient sampling designs to determine nontimber biomass on a large-scale basis for operational evaluations.
2. Improved volume tables that describe more representative biomass volumes of nontimber tree species.
3. Identification of variations in specific gravity values for different portions and components of trees and woody shrubs.
4. Reliable equations for predicting weights for trees of deliquescent form and woody shrubs of complex growth forms.
5. More species-specific estimates of heat content values to determine potential energy equivalents.

At least partially satisfying these and other research needs should greatly enhance a forester's ability to quantify nontimber biomass for energy use in the future. With increasing demands for energy of all sources, these quantifications will be imperative in the future.

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VOLUME AND BIOMASS ON GAMBEL OAK WOODLANDS

Kendall L. Johnson

ABSTRACT: Recent use of Gambel oak has been based on the attitude that it is a "nuisance" species, to be controlled as a means to increase forage production and improve tree regeneration. Now interest has arisen in oak as a fuelwood resource, underscoring the lack of management information on the type. Recent studies on Gambel oak have provided information on volume and biomass, which indicate that (1) there is sufficient stem biomass available to make Gambel oak an important fuelwood resource, (2) productivity is probably high enough to exceed economic thresholds, (3) inherent sprouting is ideal for a fuelwood management cycle, and (4) fuelwood values should be included in all management plans where Gambel oak is a component of the habitat.

INTRODUCTION

It is appropriate, yet symptomatic, for a practical range manager in a regional technical conference peopled by research foresters, biometricians, and mensurationists to address the subject of volume and biomass of Gambel oak (*Quercus gambelii*) woodlands. It is appropriate because Gambel oak lies at the interface between forest and range as *kinds* of land. Hence the ecology and productivity of the vegetation associated with Gambel oak are the legitimate concern of the range manager. The involvement is symptomatic of changing attitudes as well, because until recently range managers have dealt with the type by default: foresters have not considered Gambel oak a true wood resource but just another woody plant. Clonal species, which are as often shrubs as they are small, irregular trees, have not been of concern. In the absence of real value in the wood resource itself, aided by the indifferent forage value of the shrub (as opposed to the vegetative type), the idea developed that Gambel oak is a "nuisance" species with few redeeming values. Thus it has fallen to the range manager to set management priorities concerning it.

It should not be surprising that the hallmark of Gambel oak management to date has been its reduction or elimination as a means to increase forage production. So in a land of difficult resource use, a prominent resource has received only negative attention. Although the situation is changing, with new interest and management emphases developing, everyone interested in Gambel oak shares a common problem: the information base is extremely shallow.

A QUICK NATURAL HISTORY

Gambel oak occurs in the Four Corners States of Utah, Arizona, New Mexico, and Colorado as a dominant overstory on about 9 million acres (fig. 1) (Tiedmann and others 1983).

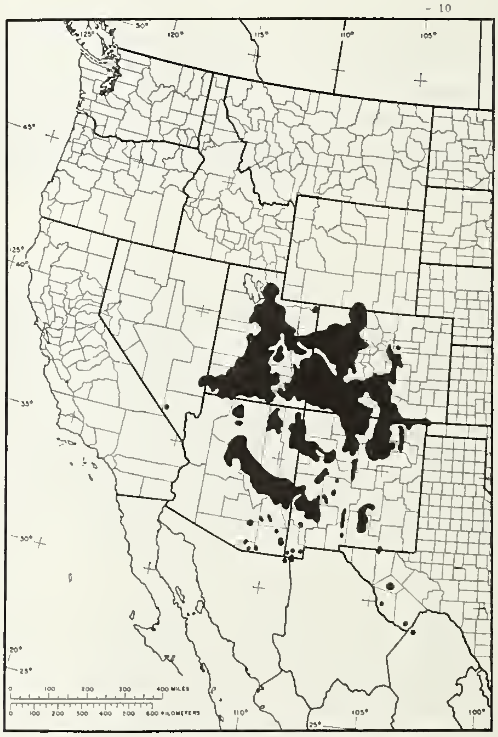

Figure 1.--Distribution of Gambel oak (Little 1971).

Its growth form is normally a multiple-stemmed clone varying from a small shrub (fig. 2) to a medium-size tree. On deeper, better-watered soils, oak can achieve a full tree form (fig. 3); the incidence of tree sizes increases with distance south in its range (Reynolds and others 1970; Barger and Ffolliott 1972). Wullstein and Neilson (1985) asserted that successful sexual reproduction of Gambel oak in northern Utah is rare, due to late spring freezes, acorn predation, and summer drought stress of seedlings. Thus Gambel oak in its northern ranges may be an artifact of an earlier, more mesic climate,

Paper based on an address presented at: Growth and Yield and Other Mensurational Tricks: A Regional Technical Conference, Logan, UT, November 6-7, 1984.

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sustained solely by its capacity for vegetative reproduction. This relation helps explain the preponderence of larger sizes in the southern ranges.

Figure 2.--Growth forms of Gambel oak; usual multiple-stemmed shrub.

Figure 3.--Growth forms of Gambel oak; occasional full tree form.

The Gambel oak type provides good winter habitat for mule deer, due to its high cover potential and plentiful acorn production. They also browse new growth and sprouts created by fire or harvest. The type is also a good livestock resource due to associated forage species. Oak itself is of only fair to poor value, and young shoots contain significant amounts of tannic acid. Poisoning, especially of cattle in the spring, is possible under conditions of heavy intake (Muenscher 1961).

The early Utah settlers used Gambel oak and other woody foothill species for fuel and fence posts. Oak soon proved to be poor fencing material, but it had superior heat-producing qualities as fuelwood (18 percent > pinyon; 24 percent > juniper) (Clary and Tiedmann 1985). This attribute ensured continuous use in the first decades of settlement, declining in later years as alternate fuels became available. Use of oak as fuelwood virtually disappeared in post-World War II years, and the species settled into its "nuisance" status for most of two decades, to be removed if possible, discouraged if not, or simply ignored.

The energy crises of the past decade have revived interest in oak as a fuelwood resource, intensified by its proximity to population centers. As a consequence, interest in management of the species as a renewable resource has also surfaced, as pointed out by Winward (1985).

THE PRESENT SITUATION

In contrast to other tree and shrub types of the Intermountain West, little is known of Gambel oak. Ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea Engelmannii*), and other species of the montane zone join pinyon-juniper (*Pinus edulis* and *Juniperous osteosperma*) as focal points of extensive bodies of literature. By contrast, the literature on Gambel oak is scant and readily plumbed. Relatively little is known about its physiology or ecology, nor even the extent or productivity of the resource. Virtually nothing is known about stand management. More is known about methods of removing Gambel oak (Parker and Ritty 1982) than about its biological status. As a consequence, Gambel oak fully merits A. R. Tiedemann's apt description, the "forgotten resource of the Intermountain West."

Recognizing the situation, the Shrub Sciences Laboratory of the Intermountain Research Station has initiated a research program. Efforts to develop an information base about Gambel oak physiology, ecology, and aspects of management are proceeding and include studies on stem and stand characters.

MEASUREMENTS OF OAK VOLUMES

Of most interest to this conference will be estimation techniques to derive volume and biomass of Gambel oak. Van Hooser and Schaefer (1985) observed that the traditional methods employed to define volumes of timber species cannot be employed on clonal species such as Gambel oak for a simple reason: lack of a well-defined central stem. This fact, combined with the low intrinsic value of the species, has forestalled direct measurements of volume and

derivation of estimation techniques. A recent study conducted in north-central Utah by Clary and Tiedemann (1985), however, has provided direct information on oak volumes and biomass.

Intensive sampling of eight plots of variable dimensions for all biomass above and below ground (live and dead) showed that stem density ranged from 2,000 to 14,000 stems per occupied acre, and that density was significantly related to stand height, but not to age, which suggests a genetic determination. Most individual clones occupied much less space than an acre at 30 to 300-ft spacing.

Biomass distribution per occupied area, derived from expansion of plot data, indicated that total live biomass approximated 111,000 lb/acre, made up of overstory stems (33 percent), branches and leaves (5 percent), underground roots, rhizomes, and lignotubers (56 percent), and associated plants (6 percent). Dead biomass totalled about 53,500 lb/acre, consisting of dead branches on live stems (15 percent), standing and down stems (23 percent), and dropped foliage and other litter (62 percent). The ratio of live to dead biomass on the study sites was 67:33; that of above- to below-ground biomass, 44:56.

Clary and Tiedmann (1985) compared these results with similar values derived from other woodlands. They found that the live above-ground biomass of approximately 24 tons/acre placed Gambel oak within the lower values found among interior West commercial forests (22-133 tons/acre) determined by Weaver and Forcella (1977). The placement was similar when only living overstory biomass was considered: 21 tons/acre. But Gambel oak differs in one significant characteristic: ratio of above- to below-ground biomass. The value of 44:56 was distinctly at variance with the mean values (83:17) of oak stands around the world reported by Santantonio and others (1977) or for other western semiarid oaks (65:35) noted by Whittaker and Niering (1975). Clary and Tiedemann (1985) suggested that the massive underground system of lignotubers, roots, and rhizomes of Gambel oak creates the difference.

Based on these data, Clary and Tiedemann (in press) developed prediction equations for stem biomass components in the relation:

$$\log Y = a + b \log X$$

where

Y = weight of ovendry biomass

X = basal stem diameter

a,b = regression coefficients

A set of graphic curves was developed from the relation to provide land managers estimates of bole biomass from the single measurement of basal diameter.

A method developed by the Forest Survey Unit of the Intermountain Station relates volume to tree attributes that are readily measurable (Van Hooser and Schaefer 1985). The technique, called visual segmentation, is based on measurement of lengths and midpoint diameters of all uniform segments (visually defined) of stems and branches within size classes, usually 2-ft lengths and 2-inch diameters. Tree volume is then developed by summing the individual segments. Regression analysis of plot data yielded the equation:

$$V = a(D^2H)^b$$

where

V = volume in cubic feet

D = basal diameter in inches (outside bark)

H = height in feet

a,b = regression coefficients

Tests of the visual segmentation technique on species with irregular stems such as juniper have established that it produces reliable estimates of volume. Extension of the technique to a clonal species like Gambel oak will require clonal attributes in the relation, that is, average stem diameter and height, stem density, and clone basal area. To date this has not been done; hence there is no readily usable method of estimating Gambel oak volumes on a survey basis.

THE FUELWOOD RESOURCE

Applying biomass estimates to Gambel oak stands yields a first approximation of fuelwood values. On the basis of their study, Clary and Tiedemann (1985) estimated that bole wood volumes ranged from 7 to 14 cords per acre. In a study of the economics of using Gambel oak for fuelwood, Wagstaff (1985) found that minimum harvest size (set at 3.5 inches diameter) was reached in about 65 years among clones of oak at six locations in north-central Utah. The annual increment of growth declined rapidly at younger ages and leveled out at about 2 percent annually after minimum harvest size was reached. Based on current retail prices of oak firewood and estimated costs of harvesting, Wagstaff (1985) found that stumpage prices of oak clones ranged from \$115 to \$2,300 per stocked acre. These values indicated that Gambel oak can be successfully managed for fuelwood where markets exist and competitive uses of land are limited. The economic value of the standing crop of wood is significant. Studies conducted by Tiedemann and others (1983) indicate a value of approximately one billion dollars if 10 percent of the habitat could be managed for fuelwood production. Use of Gambel oak lands as wood-producing sites may well be more valuable than any other use.

CONCLUSIONS

Although the wood resource represented by the Gambel oak type of the Intermountain West remains poorly defined, enough information is at hand to

draw the conclusions that (1) there is sufficient stem biomass available to make Gambel oak an important fuelwood, (2) productivity is probably high enough to exceed economic thresholds, (3) its profuse sprouting is ideal for a fuelwood management cycle, and (4) fuelwood values should be included in all management plans.

The Gambel oak type will continue to provide an important forage resource for livestock and big game, but in an age of increased pressure on natural resources within a heightened environmental awareness, concentration on single values is no longer appropriate. Gambel oak has high potential to produce fuelwood, forage, and wildlife habitat values concurrently, requiring a high degree of cooperation and coordination in developing appropriate management plans.

Too little information, especially on stand management techniques, is available to achieve true multiple-use management immediately or even soon, but Gambel oak is ready to take its place among interior West resource values. Range managers invite foresters generally, and mensurationists particularly, to help define that place. The "forgotten resource" has been discovered.

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FOREST METRICS: ARE WE THERE? WHERE DO WE GO FROM HERE?

James D. Arney

ABSTRACT: Comments on state of the art in forest mensuration focus on sampling and growth modeling. In the area of sampling, discussion emphasizes standing inventory, growth and mortality, site productivity, and stem volume. Growth modeling is discussed in the context of demands by users for yield information and in the context of the kind and amount of data available to develop these models. Recommendations are based on input from presentations in this conference.

INTRODUCTION

The views presented over the last 2 days make it clear what is possible in the development and implementation of mensurational technology; however, varying approaches, budgets, and objectives have meant that not all of us are applying the same methods. This is as it should be. We have also recognized these last 2 days that most of us are not where we would like to be.

In this presentation, I would like to identify the mensurational techniques that offer the most promise for getting us to where we could be. The discussion of sampling and growth modeling techniques will be followed by a list of my recommendations on where we go from here.

SAMPLING

In sampling for standing inventory and for growth ("change"), our needs are evolving and becoming more specific. The continuous forest inventory (CFI) plot designs are no longer adequate, and we are moving toward computer-based geographic information systems with specific details about the character of each stand in the inventory. Figure 1 illustrates the detail now required for each stand. Our harvest scheduling and silvicultural planning activities demand knowledge of species mixes, size distributions, merchantable yields, defect reductions, stand vigor and health, stand density, age, distance to mill, logging operability, and season of access.

These details are most efficiently obtained by sampling within stands using temporary variable-density plots. Measurements must be included for height and crown ratio within tallied diameter classes by species. Stands are typically 10 to 300 acres and are resampled on a 5 to 10 year schedule. Intermediate inventory reports are provided using growth model updates. Sampling for inventory data bases includes all commercial species in the stand without regard to current merchantable dimensional limits. Permanent plots and growth from increment cores are not cost effective in sampling for stand-based inventories.

PACIFIC NW REGION — OPERATING UNIT 4
FOREST YIELD REPORT — RESOURCE INVENTORY SYSTEM (RIS) — STAND NUMBER 2372
TOTAL ACRES 132 — SITE INDEX 87DF
TIMBER TYPE WHDF — TOTAL AGE (YRS) 90
EXAMPLE REPORT FOR UTAH CONFERENCE

BH SP AGE	DBH	TREES /ACRE	BASAL AREA	HEIGHT	CROWN RATIO	TOTAL CUFT	MERCH CUFT	MERCH BDFT	NET BDFT	#LOGS /MBF	LOG DIB
					** VALUES ON A PER ACRE BASIS **						
	8	2	0.7	93.0	47	29	0	0	0	0	0
	9	5	2.1	100.1	51	90	0	0	0	0	0
	11	37	25.6	107.1	54	1144	1070	5503	5118	33.0	8.1
	14	46	46.9	107.6	54	2099	2010	11040	10267	22.0	9.6
DF 80	12.3	90	75.3	107.6	54	3362	3080	16543	15385	25.7	9.0
	10	34	16.9	106.8	67	767	687	3400	2822	40.3	7.5
	13	120	102.4	112.3	69	4881	4619	25036	20760	23.5	9.4
	15	41	50.2	114.2	69	2433	2340	12710	10549	17.2	10.9
WH 81	12.5	195	169.6	114.2	69	8081	7646	41146	34151	22.9	9.5
ALL	12.4	285	244.9	111.9	64	11443	10727	57689	49536	23.7	9.4

CCF=397 STUMP HT. 1.0 LOG LENGTH 16.4 TOP DIB 5.0 MIN DBH 9.0

Figure 1.--Example inventory report for 90-year-old stand.

We sample for growth and mortality in order to assign portions of the change that occurs from one inventory measurement to the next to different components of growth, ingrowth, growth on mortality, and mortality. Plots are permanently located, either fixed-area or variable in design, all trees are tagged, and measurements minimally include diameter at breast height (d.b.h.), tree height, crown ratio, and species. As seen in figure 2, volume change for the measurement interval may be defined into survivor growth, growth on mortality, ingrowth, and loss due to mortality. Distribution of these permanent growth plots is independent of the standing inventory samples described earlier, and the objectives are very different. These permanent plots must provide a data base that equally represents all species across all site productivity classes for the range of stand densities and size distributions that currently exist or that managers are moving toward. This data base

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is the basis upon which the growth update model is developed.

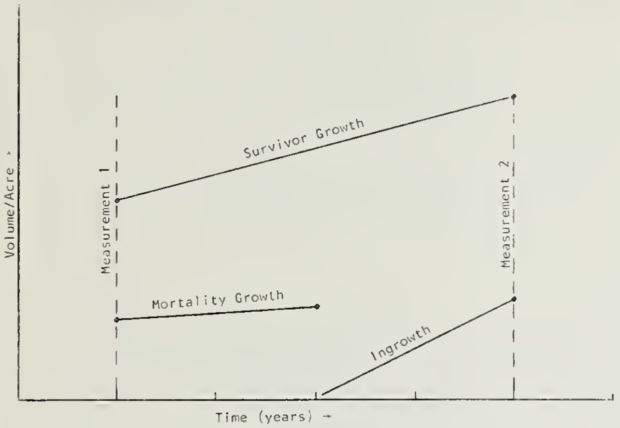

Figure 2.--Components of change from growth trend studies.

In sampling for site productivity, we require another geographic stratification independent of the forest inventory discussed earlier, and again a geographic information system is heavily utilized. Productivity has been stratified by standing volume, growth, site index, and habitat in this region. My experience has been that we place the greatest confidence on a field-observable index that is easily and repeatedly obtainable by different observers. Tree site index is the site productivity index of choice. To be used effectively, the base reference age for all species in the West should be converted to 50 years measured at breast height. We are not managing stands to rotations of 100 years or longer; therefore, a 100-year base is no longer observable. Costly stem analyses are not needed if we apply Boris Zeide's (1978) growth type concept (fig. 3). I recommend field measurements

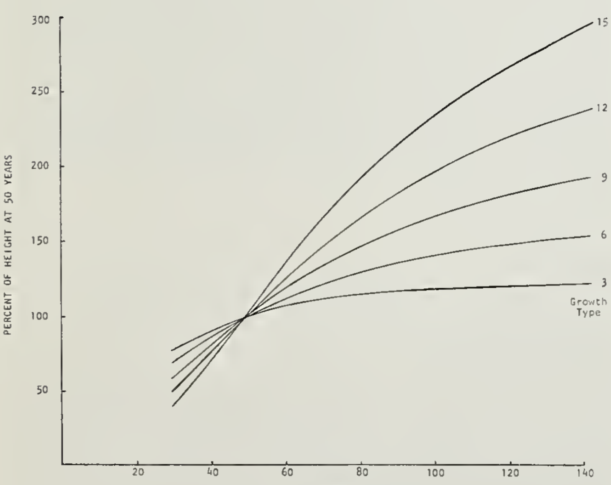

Figure 3.--Shape of height growth types.

of total height above breast height at 30 and 60 years on at least three trees for each species at each sampling location. Height at 50 years from the growth type curve is the reference site index. Differences in site index among species at the same location are used in the growth projection model to drive species-specific growth equations. Currently available site index curves for major species in the West have a range of growth types as displayed in figure 4.

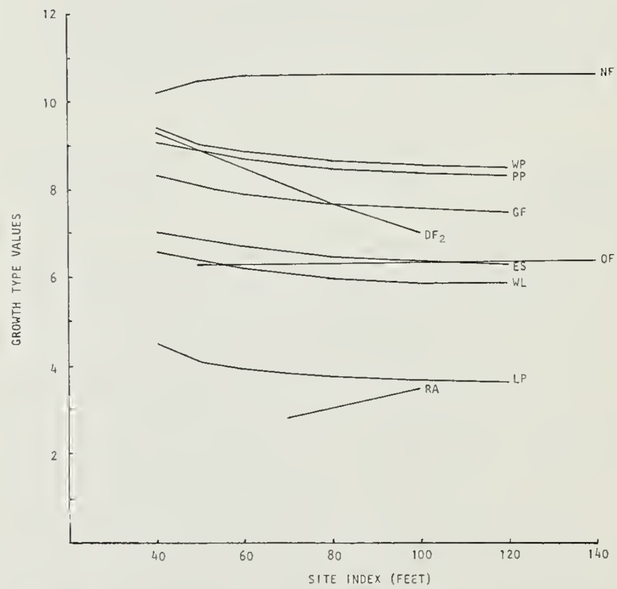

Figure 4.--Trends in growth types for published site curves.

Since not all of our lands have healthy, free-growing 60-year-old trees on them, a number of other soil and climate parameters should be recorded at each site-tree measurement location. These parameters should include annual precipitation, elevation, aspect, slope, soil depth, and soil parent material. Strong correlations have been found between these parameters and site index. An index of site productivity may then be assigned to all stands in the inventory regardless of their age or vigor. In addition to providing an effective means of estimating site index, these parameters have been found to be correlated with the growth type values. This provides not only a location-specific productivity index, but also a location-specific growth shape index for the yield projection of each stand.

It is apparent that our silvicultural planning activities are much more demanding of an inventory data base than ever before. One more sample design is needed, that is for the development of taper equations for all commercial species. Hardly a month goes by that inventory and yield projection reports are not generated for at least two alternative merchantability specifications. Whole tree volume equations and tariff tables are no longer adequate. The whole

bole taper equation system by Damaerschalk and Kozak (1977) works well and has been fit to 16 species in British Columbia.

GROWTH MODELS

Our demands on growth models have changed in recent years. As with the standing inventory report, we need clear descriptions of species mixes, size distributions, merchantable yields, defect distribution, stand vigor, and stand density (fig. 5). Growth models must provide stand table distributions and taper functions by species. Growth functions must perform in a stable manner at any age, density, or treatment. Stand average models are no longer sufficient.

PACIFIC NW REGION
FOREST YIELD REPORT — STAND PROJECTION SYSTEM (SPS) — SITE INDEX 87 DF
VERSION 84.01 — BASE- 50 YRS BH AGE
TOTAL AGE (YRS) 90

EXAMPLE REPORT FOR UTAN CONFERENCE

SP	BH AGE	DBH	TREES /ACRE	BASAL AREA	HEIGHT	CROWN RATIO	TOTAL CUFT	MERCH CUFT	MERCH BDFT	NET BDFT	#LOGS /MBF	LOG DIB
					** VALUES ON A PER ACRE BASIS **							
		8	2	0.7	93.0	47	29	0	0	0	0	0
		9	5	2.1	100.1	51	90	0	0	0	0	0
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		14	46	46.9	107.6	54	2099	2010	11040	10267	22.0	9.6
DF	80	12.3	90	75.3	107.6	54	3362	3080	16543	15385	25.7	9.0
		10	34	16.9	106.6	67	767	687	3400	2822	40.3	7.5
		13	120	102.4	112.3	69	4881	4619	25036	20780	23.5	9.4
		15	41	50.2	114.2	69	2433	2340	12710	10549	17.2	10.9
WH	81	12.5	195	169.6	114.2	69	8081	7646	41146	34151	22.9	9.5
ALL		12.4	285	244.9	111.9	64	11443	10727	57689	49536	23.7	9.4

CCF=397   STUMP HT. 1.0   LOG LENGTH 16.4   TOP DIB 5.0   MIN DBH 9.0

Figure 5.--Example yield table report for a 90-year-old stand.

The tree-list model is easier to develop and is more robust than a stand model. We have observations of open-grown trees and we have observations of suppressed trees. All that is required is to provide a model of potential growth rate for open-grown trees and then apply a modifier function for relative position in the stand and a modifier function for stand density as in figure 6. Growth models of this type are available. Yields are most often projected from stand models through extrapolation; interpolation is most often used to project yield from a tree-list model.

Tree-list models are biologically simplistic and provide us the opportunity to draw more information from existing permanent plot studies than analyses for stand average models. For this reason I disagree with the statement made earlier in this conference that "modelers are more plentiful than good data." There are a significant number of silvicultural and growth trend studies for our major commercial species throughout the West, and we have not fully used these studies in modeling for growth and yield. Installing new studies should come second to a more vigorous attempt at using existing data.

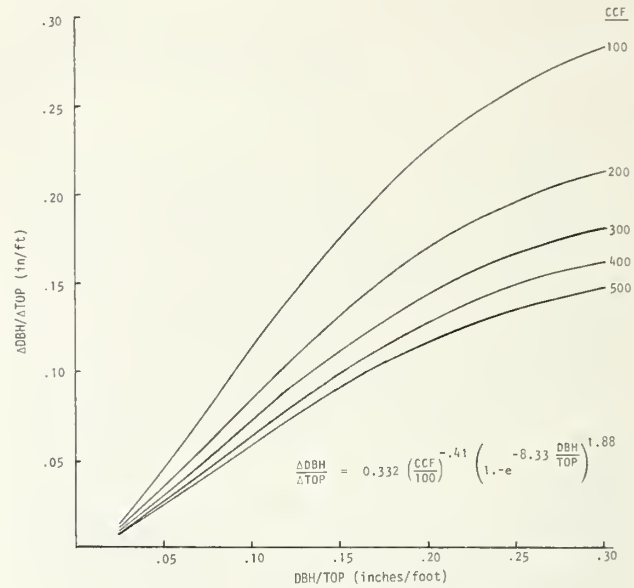

Figure 6.--Relationship between predicted growth and relative size and density.

About the availability of modelers! A good model, as stated earlier by Curtis and Hyink, requires good biological as well as mensurational knowledge. In my view, this comes from a team of mensurationists, silviculturists, soil specialists, and others. In the last 10 years, for a variety of reasons, we have moved away from these kinds of team reseach programs. Other professions are expanding their use of interdisciplinary teams successfully. Avenues open to us are group contract, cooperative research programs, or both. No really good prototype exists for us to follow. Existing cooperatives have been too weak on analytical studies and too heavy on measuring more trees. The new Inland Northwest Growth and Yield Cooperative (1984) has the potential to develop a strong analytical approach to growth modeling. It is being used as a prototype for similar cooperatives in the Canadian Provinces. If these cooperative research programs are successful, we should see a marked improvement in the flow of mensurational technology over the next few years.

RECOMMENDATIONS

I would like to close with the following recommendations:

1. Do not mix inventory plots with growth plots.
2. Inventory includes volume, vigor, and defect by species and diameter class.
3. Record site index for all species on a 50-year d.b.h. age basis.
4. Stratify your ownership using soil-site and growth-type relationships.

5. Apply taper equations in all volume calculations.

6. Record change on growth plots as survivor growth, ingrowth, and mortality.

7. Consider tree growth models as the preferred stand projection approach.

8. Take advantage of contract research and cooperative programs to supplement in-house programs.

9. Utilize existing data to the fullest extent before establishing new installations.

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COLLECTING GROWTH AND YIELD DATA: A CONTRACTOR'S OPINION

Gordon L. Younker

ABSTRACT: AAA Engineering and Drafting, Inc., presents three points regarding mapping and data collection contracting: (1) Invitation for Bid procurement often compromises data quality by ignoring other critical contractor characteristics. (2) Many government agencies do not recognize the advantages of outside contracts, which often produce increased quality at lower cost. (3) Outside contractors can sometimes share relevant experience and thus eliminate the need for a government agency to repeat steps that have already been taken by others.

INTRODUCTION

AAA Engineering and Drafting, Inc. (AAA) offers the perspective of a contractor who has gathered forest data according to detailed contract specifications designed by government foresters and contracting officers. In the last 10 years, AAA has been awarded and has completed 59 forestry inventories and mapping projects on 42 Forests throughout the United States. Projects have included timber and vegetative delineation and classification of aerial photography, forest mapping, and continuous forest inventories. Forestry inventories have included the establishment of permanent plots and the remeasurement of plots established in earlier inventories. Presently, AAA is remeasuring pinyon-juniper fifth-acre plots, including woodland volume estimates using the visual segmentation technique.

During the last 5 years, AAA's employment has grown from 80 to 150 professionals and technicians. AAA's major emphasis continues to be mapping, with 70 percent of the corporation's current business with the Defense Mapping Agency.

THREE CONCERNS

The following three points are concerns of AAA as relates to the contracting for mapping and data collection.

1. AAA believes that the quality of data, which is the basis for effective growth and yield models and which has been referred to numerous times here, is too often compromised by the Invitation for Bid (IFB) procurement or "lowest offer gets the project" contracting. Though competition and costs are of tremendous importance, neither should be sought at the expense of good data. The often-used adage "you get what you pay for" should be considered when contracting for these services. The Request for Proposals (RFP) procurement encourages competition and enables selection of a qualified contractor. Though prices are moderately higher than under a low-bidding procurement, they are reasonable for the services required. Under the low-bid system, the government sometimes spends more money inspecting the contractor's work than the contractor is paid for the services. Although RFP procurement enables the government to consider both a contractor's qualifications and offered price, when exact and proven specifications become available contracts are often awarded solely on the basis of low bidding. In these situations specifications should include strict qualification standards and performance bonds. Overall, large projects will yield better data if contracted to one contractor than if split among many different contractors.

2. In these times of reduced budgets, some agencies still resist contracting for forest data gathering services, believing that only menial tasks should be contracted outside the government and university environments. Apparently, the basis for this practice is the belief that outsiders, including the small business community, cannot be trusted or will reduce the government employee's job security and responsibility. In fact, aggressive Regions and Forests have successfully contracted for years; the results have been increased quality and significantly lower costs than traditional government programs. AAA believes even greater opportunity exists to maximize the services needed to manage resources within the dollars available, if contract services are procured and procured properly. Many more services could and should be contracted.

Good contract specifications allow the government to maintain tighter quality control than is possible with force account or in-house crews. The total cost to the government of contracting a project is approximately one half the cost of the same work when completed by government force account crews. This total cost comparison considers both the contract price and cost of the government to administer the contract. The much reduced cost of contracting should in itself result in serious consideration for procuring a contractor's services.

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3. There are a few writing contracts who think their project is the first of its kind. They seem to begin their contracting programs from scratch, learning the right ways only after bad experiences. Often, as close as the Forest or Region next door, similar contract experience and programs exist. AAA was impressed by the Rome-headquartered FAO forester who requested AAA copies of past Forest Service and BIA contract specifications for forest mapping and inventory to help design a contract program to complete similar work in the Caribbean.

A CHANCE TO SHARE

AAA Engineering and Drafting, Inc. (AAA) welcomes the opportunity to share its contracting experience with those here at home in the United States as well. AAA has become acquainted with many in attendance at this conference through its contracts with a variety of Government agencies. We are glad for these opportunities to provide service within the profession and appreciate the professionalism we have found.

245 GROWTH AND YIELD MODELING: WHERE DO WE GO FROM HERE?

Alan G. McQuillan

ABSTRACT: This paper focuses on the need to establish permanent plots but identifies the numerous problems associated with them, ranging from which variables to measure, designing and stratifying the sampling system, obtaining adequate funding, data collection problems, resistance to change in approaches, and statistical reliability to discontinuity in personnel, policy, and funding. Proposed solutions include support from top personnel and organizational policy to prohibit external interferences in and around permanent plots and a cooperative administrative effort to ensure continuity of personnel, policy, and funding. Miscellaneous responses to issues raised at the conference are also included.

INTRODUCTION

I would like to respond to some of the papers we have heard in the last 2 days . I liked John Teply's remarks on the need for reconciliation between successive inventories. In academic environments we are usually concerned with continually trying to find new and better ways to design the wheel, but from my industry experience I know that when we come out with a new timber inventory there are always questions asking us to explain the differences between the new and the old inventories. When sampling procedures, volume equations, and other methodologies have been changed, this is not always easy.

I liked all of Ralph Johnson's remarks on the problems of calibrating models for new areas, gaining user acceptance, finding out what is really going on in a new area, and especially the importance of quality software maintenance. This last item is all too often ignored. I have worked on Forest Service contracts to provide software, usually economic software, and I always had the feeling that once these models were delivered they would not ever be used, because as soon as the recipient begins to work with a new piece of software, he starts to find changes that he would like to make. Often when relatively small models are provided under contract, the project is completed, the program is wrapped and tied with a ribbon and delivered, and that is the end of the contractual obligations. There are no provisions, and it would be very difficult to make provisions in some cases, for the modeler to come back periodically and change the program as needed. Hence, these things end up on a shelf gathering dust. I read in one of the computer journals that nationwide about 50 percent of all software costs are for maintenance, which illustrates just how important software maintenance is.

I liked Bill Wykoff's definition of that illusory thing that we call a timber stand. If I remember correctly, Bill referred to a stand as a unit of land that is comprehensible to other specialists. This is probably about as close as we can hope to come to a precise definition.

I learned from Charles Chambers why Beers' method of using variable plots for growth measurement is unbiased. I always had the feeling that it was all right to ignore ongrowth trees, but now I know the exact rationale for doing this. And I learned from Roger Chapman about the bias that enters when current tree diameters are used with variable plots to estimate growth. This is a mistake that I have made in the past, and I did not realize it until yesterday.

SEPARATE MODELS?

This morning I was spurred once more to thinking about the problems of volume estimation, and the more I think about it the more I become convinced that we should explicitly separate growth models from volume estimation routines. That is, when doing growth modeling we should concentrate on making projections in terms of tree characteristics.

Specifically, we need to produce tree lists or stand tables showing number of trees by species and d.b.h. classes. Then we should endeavor to superimpose height information in the form of mean height for each d.b.h. class or, preferably, in the form of a height distribution within each d.b.h. class. If this gets too complicated, a tree list would suffice.

With a detailed stand table or tree list in hand, we can then worry about the entirely separate problem of volume computation. Ecologists, energy specialists, and other people interested in fiber yields can worry about generating cubic volume or biomass weight from a tree list or stand table; salespeople can worry about cruise volume or Scribner scale in terms of 16½-ft logs. For industry people, scale using a standard log length is usually not meaningful, but they can take stand table or tree list information and apply taper equations to feed utilization and bucking simulation models to estimate actual product recovery from the inventory or stand growth projections.

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PERMANENT PLOTS

Finally, I heard a lot of talk yesterday about permanent plots. It seems that everybody is renewing their interest in permanent plot installations for growth model validation or improvement. Some growth data can be obtained from destructive sampling such as height growth and d.b.h. increment, but some things can only be reliably tracked using permanent plots. This is especially true of mortality data. It is also true for crown ratios. It might be possible to reconstruct past crown ratios using stem analysis data, but it would be very difficult . Yesterday there seemed to be unanimous concurrence on the need for a system of permanent growth plots, and I would agree.

I am somewhat disturbed, however, at the prospect of people rushing out to install their own systems of permanent plots, although that may be inevitable. Every organization has its own specific needs with respect to growth information, its own ideas, and its own constraints on the nature of permanent plot installations. The lack of permanent plot data in the northern Rockies today is not entirely due to a lack of plot establishment in the past. From evidence I have encountered, I have gained the impression that many so-called permanent plots have been established in this region in the last 50 years; however, there has been much attrition in the permanent plot data base. This follows naturally for many reasons and can undermine the usefulness of permanent plots for long-term growth monitoring.

What are the problems with permanent plots? There are many.

1. There is the problem of which variables to measure, and fashion regarding this changes. For example, although crown ratio is a popular proxy measure for tree vigor today, I inherited a set of permanent plots on which crown ratio had not been measured because at the time the plots were designed nobody thought crown ratio was important. So now we go out and superimpose crown ratio measurements on these plots. By tomorrow, or 5 or 10 years from now, we will undoubtedly have discovered new tricks and new variables which we feel give us a better handle on growth prediction. At present, there is frequent discussion of measuring sapwood basal area. Should we measure it or not? The only safe course is probably to measure everything that we can think of and to map the trees as well, but it becomes difficult to justify the expense to managers when we are not sure what is needed. Even if we do measure everything we can think of, we will still not have enough data because future researchers will undoubtedly think of new things.

2. There is a problem keeping harvesting out of permanent plots. This might sound like a simple problem, but it is not always easy to solve.

3. There is a problem finding permanent plots for subsequent remeasurement. I have been involved in quite a few projects where a large number of plots measured previously could not be located for remeasurement in a cost-effective manner.

4. There is a problem designing the sampling system and the stratification used for laying out the plots. Whatever system we decide upon, we will no doubt find in retrospect that it compromises what we later try to do with the plot information.

5. There is the obvious problem of inadequate and discontinuous funding (which I shall return to later). Adequate initial funding is necessary, as is continued funding, because although some permanent plot data are useful immediately, the real gains accrue only over several decades.

6. There is a problem obtaining quality data. Data used for growth research must be of a higher quality than that used for point-in-time inventories. This problem is not peculiar to permanent plots, but when we measure plots, there can be inconsistency between the quality of data obtained in one time period and the next. We heard references yesterday to the problem of obtaining accurate height measurement.

7. There are some peculiar problems related to the technology of record keeping. In the 5 or 10 years between measurements, significant changes have usually been made to the computer systems; this makes necessary reformatting or some other data manipulation.

8. There is the problem of deciding which trees to measure. What minimum d.b.h. will we use? Will we measure small trees on a smaller plot and large trees on a larger plot? Will all trees, especially small trees, be numbered? We usually cannot afford to measure all small trees on the same plot size used for large trees and cannot afford to individually tag and number all small trees. Yet if we do not, the problems of accounting for ingrowth and ongrowth and differentiating these from simple coding or measurement errors can be substantial.

9. The value of a permanent data base will decrease if there is not substantial and continued resistance to changing the plot measurement system. From one measurement to the next there is often pressure to drop certain variables which have gone out of fashion and to save time by so doing. Because we never really know which variables are going to stay out of fashion and which ones might come back, it is dangerous to drop variables simply because current thinking suggests they are no longer useful. In addition, entire plots are dropped if they no longer seem to be of interest. The concept of what we mean by managed stands can change radically from one decade to the next. As economic conditions worsen, interest in natural regeneration with little or no site preparation

can rebound, and we might regret decisions which assume that intensive forestry is the name of the future game. There are also obvious problems with changing measurement procedures and skipping measurements. Another important problem is the tendency of researchers to squeeze as much information out of the system as possible and thus to superimpose new treatments on an existing permanent plot data base. For example, they may suggest that half the plots should be fertilized or the trees pruned. It does not require many new levels of treatment on a data base to destroy the integrity of the entire system.

10. There is a problem achieving statistical reliability when growth estimates are calculated as the difference between two point-in-time inventories, each with its own error characteristics. If we measure height plus or minus 2 ft the first time and again plus or minus 2 ft the second time, and if these measurements are 5 years apart, we may generate the kind of problem I'm talking about. Say the tree actually grew 5 ft in 5 years and the first measurement was 2 ft high and the second measurement was 2 ft low: we would conclude that the tree had only grown 1 ft over the 5-year period--a substantial error. I have looked at more than a few permanent plots where trees apparently shrunk over time.

11. A major problem relates to discontinuity for personnel, motivation, interest, and funding. Maintaining permanent plots is not a job to be foisted upon reluctant personnel unless they are to be adequately recompensed and recognized for their efforts in this regard. I shall return to this later.

None of these problems indicate that we should not install permanent plots. We need to. But if we are to spend a lot of money on them, we should seriously consider ways to overcome the problems I have described; otherwise our money is probably wasted.

Standards Needed

Regarding variables, plot size, sample design, and so on, we should get together on some agreed upon standards. Then data from different organizations would be compatible, and the whole would amount to more than the sum of the parts. Bob Curtis was probably right when he said the plots should be large.

Establishing permanent plots requires motivation and support from people high up in the organization because their endorsement is critical if we are to prohibit harvesting in and around plots and other external interferences. We need administrative weight behind these prohibitions, and even this will not be enough because top personnel and organizational policy change over time. Unfortunately, there isn't any way to prevent this. Ideally we need to be protected by a set of procedures that is akin to the U.S. Constitution. Changes or discontinuities in the permanent plot system would thus be difficult to accomplish without the concurrence of almost all interested parties.

I do not know how to do this administratively. A cooperative, such as the recently formed Inland Northwest Growth and Yield Cooperative, could help achieve continuity and control, but only if we could ensure the cooperative's longevity, which is not an easy task.

We also need secure funding, which is probably the most difficult of all to achieve, as I'm sure everyone here realizes. Ideally we would establish a trust fund, the interest from which would be used to fund remeasurement and data base maintenance. This would prevent long-term permanent plot study disruptions caused by short-term budget crunches and other crises. In addition, we should employ someone whose career success depends on the success of the permanent plot system.

Continuity Is Central

These ideas might sound expensive and unrealistic. Cooperative administration might make them less so if expenses and personnel were shared. The continuity of this arrangement would, of course, be central.

If these proposals sound too much like pie in the sky, we must ask ourselves how badly we really want permanent plots. There is not much point establishing a myriad of plots in the vague hope that some of them will survive to be remeasured for the next 50 years. If we really need the permanent plots, we should seriously seek ways to ensure their longevity and increasing usefulness. If we are trying to fund the project on a shoestring, it probably will not survive and we are probably wasting whatever little money and considerable effort we are spending on establishing the plots in the first place. This has happened in the past, and there is nothing to prevent its happening again.

I would like to see future discussion of the permanent plot question focus on ways that might ensure, or at least increase, the chances for such a program to succeed.

245 GROWTH, YIELD, AND MENSURATION:

A FEDERAL USER'S PERSPECTIVE

Milo J. Larson

ABSTRACT: Users are faced with an array of techniques to help them quantify timber information and to use it for projections. The amount of choice has advantages but at the same time impedes the flow and understanding of information.

INTRODUCTION

Within any level of an organization, there are almost as many perspectives as there are individuals responsible for the work. Each mensurationist has his or her own perspective. All of these perspectives are difficult to judge objectively and are often not well articulated. In many cases, resource managers must generalize about highly variable situations without benefit of any measurements whatsoever. The information presented here consists of just such generalizations about problems in the mensuration of growth and yield.

GROWTH AND YIELD

Yields are now projected almost exclusively by models. Growth is measured, but often is not used for much unless it is required as an input for a model. Some of the models in use in the Rocky Mountains are discussed in the following sections.

RMYLD And Its Variations

This model is a whole stand model that has proved useful for making silvicultural comparisons for even-aged stands. It is simple, easy, and inexpensive to run, and hundreds of alternatives can quickly be generated by it. Although it is used in Forest Planning, it has several drawbacks: built-in assumptions for a relatively high intensity of management; inability to closely match inventoried volumes at the starting point for projection; much wider variation within a summarized inventory strata than in stands selected as a basis for the model; and the inability to project variations in species composition or diameter distribution.

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R-2 GROW

R-2 GROW is a diameter class model derived from Region 2 inventory data. The model is simple to run. It can simulate even-aged management and roughly simulate uneven-aged management. It has proven to be a good model for projecting existing inventory summaries. It can be used for projecting silvicultural alternatives in individual stand prescriptions, but it is not designed for individual stands and its data for seedlings and saplings are poor.

Stand Prognosis Model

This individual tree model has been discussed fairly extensively at this workshop. I have little to add except that it has been a good model for stand projection and for planning projections. Its drawbacks are that it is data demanding, and elaborate calculations are needed to make the projections.

PIPO

PIPO is a model that has been useful in Regions 2 and 3 to make stand projections for even-aged ponderosa pine. It has not been used in land management planning. It has some of the drawbacks inherent in RMYLD and, in addition, the only versions I have used are interactive with the computer, which is a great inconvenience if many projections and stands are involved.

ECOSIM

This model is an individual tree model patterned after the STEMS model. Region 3 planning teams like this model because it is possible to generate joint production functions for use in planning. It has been little used for individual stand projections. There has been some argument over the veracity of the projections, but our experience indicates that reasonable projections are obtained. It also requires some fairly complex calculations and has been known to bring the Fort Collins Computer to its knees when large numbers of runs are needed.

Models In General

The assortment of models and additional models in the works, such as the GEM model proposed by the

Rocky Mountain Station, offer advantages to the manager but also present a dilemma because none seems entirely applicable in a given situation. Each requires different data as input. Most disconcerting to the user is the number of advocates and detractors within the mensuration community for each model.

VOLUME AND BIOMASS DETERMINATION

Presentations here have focused on various techniques for different classes of trees and species. From the user's point of view it is essential to base estimates on parameters that are easily, routinely, and consistently measurable. The variables are, after all, abstractions of reality. When mensurationists emphasize variables too much, the result is to make plot taking exceedingly costly and prone to error.

Timber mensurationists treat forked trees differently than woodland mensurationists. The mensurationist finds he or she can improve the fit by using a height to live limb ratio on one species but not on another, and so on. From the user's point of view, if it is made out of wood and can eventually get to a certain size, it's a tree. We are not happy with tally sheets a yard long and instruction packages 2 inches thick. We are not interested in having a research plot at each sample point. We have too many situations to sample and tend to cope with rather large sampling errors. Words like consistent, simple, fast, and inexpensive loom large in an era of budget cuts.

Another area of concern is volume equations. Volume equations have been developed over and over again for the same species. Countless trees have been felled or otherwise segmented, yet we seldom have the equation we want or need. If we had the base data itself and a somewhat consistent methodology for doing the field measurements, the equations could be upgraded with far less cost and much better results. It may be a lot to ask, but we should develop such a procedure and follow it.

BALANCING MEASUREMENT PRECISION AGAINST THE GUESSES

As a user, it seems that we sometimes go overboard on precise measurements of what we can measure and then add, subtract, multiply or divide by factors that can only be derived by guess work. It is probably one of the bigger weaknesses in users.

How closely should you project growth when you have to guess at mortality? How closely do you have to measure trees on cruise plots when the observed defect is mostly guesswork, the unobserved defect is totally guesswork, and breakage is a decree by the Supervisor's Office? I don't know the answers to these questions, but I can't escape the feeling that we often measure much too closely for the estimate required. Are both users and mensurationists prone to the trap of "Because it is possible, it must be necessary"?

ADMINISTRATIVE BARRIERS

One of the major road blocks to progress in the areas we are talking about is the tendency of each administrative jurisdiction to develop its own bag of tricks. Each school, each agency, each unit within an agency tends to go its own way for measurements and growth estimations if personnel have the skills to do it. Individually, the methods may be good. Collectively, they create confusion and retard the flow of information. When you look at a given process, such as cruising or stand examination, you find striking similarities and many procedures are almost identical. In a computer age, however, the situation poses a problem. To a computer, "almost identical" and "totally dissimilar" are equally unusable.

There are encouraging signs, such as the spread of the Stand Prognosis Model and recent efforts to coordinate examination and inventory procedures between Regions 2 and 3 of the Forest Service. Although the advantages of standardization need to be weighed against the advantages of custom-designed approaches, I see increased standardization as a way to get better answers with less work in many situations.

TECHNOLOGICAL ADVANCES

Electronic data recording and decentralized data processing are rapidly approaching and should greatly enhance the ability of field units to handle mensurational work. Nevertheless, most field units still do not have the hardware they need, and most higher headquarters have not completed software or instructions needed to make it go. It also seems likely that we are vulnerable to a lot of wheel spinning as these devices are acquired. The "no two alike" situation seems unavoidable until the shakedown period passes. Hopefully, we can minimize the time, expense, and frustration of this interim period.

SUMMARY

Many mensurational tools and techniques are available for users in meeting their information needs. The array enables use of tools to meet many specific needs and situations. At the same time inconsistency and lack of standardization make comparisons of measured data very difficult. Effort by the mensurationists to maintain or improve standardization of both measurements taken and the summarized data will be greatly appreciated.

245 NATURAL RESOURCE ASSESSMENT FROM A STATE PERSPECTIVE

T. Michael Hart

ABSTRACT: Managers of public lands, especially those administered by State agencies, must be able to justify the expenditure of program funds. Often the questions asked of these managers are not easy to answer based on resource values alone. Thus, the methods used to develop viable resource plans must be quantitative rather than speculative and must be able to accommodate modification to meet local needs.

INTRODUCTION

All of us, as land managers, are being asked by the users of the land we manage and by our funding sources to describe the total resource that has been placed in our care, and explain the logic of our management decisions. Our ability to determine present and predict future supplies of natural products, and to predict future consequences of present land management decisions, depends upon measurements and models predicting volume, biomass, growth, and yield.

THREE KEY QUESTIONS

Describing natural resources to answer the question, "Where do the resources occur and what do they look like?" usually involves preparing maps and statistics. Vegetation must be described by species, size distribution, numbers, acres occupied, and by the ecological relationship of plant and animal communities to each other. Normal successional patterns are also an important factor in describing our resources.

The next question often asked, "What are the resources good for?" often requires converting the "where and what" assessment into products and dollars. This includes values relating to recreation, wildlife, grazing, forage, and fiber production. The values are constantly fluctuating, as is the "use" of the resources themselves.

An excellent example of this in Arizona is the sudden, rather unexpected, demand for fuelwood from the pinyon-juniper and mesquite areas of the State. A market suddenly existed for tree species that had in the past been considered a detriment to other wildland uses and values.

The last question asked by our users and funding sources that we must address is, "What resource changes are taking place, both natural and human-caused, and what are the consequences of the changes?" Changes considered include normal growth, and mortality resulting from fire, insects and disease, and windthrow. Human-caused changes such as logging, thinning, planting, results of prescribed fire, and urbanization must also be evaluated.

PLANNING NEEDS

Most of the State forestry organizations of the Nation are presently in the process of developing State Forest Resource Plans. The Plans must consider forest production from all ownerships and how they relate to the economic development of the State. The key to a viable resource plan is to have an accurate State-wide assessment of current supply of all forest resources, not traditional wood products only. Resource plans also must predict demand, examine management alternatives, analyze benefits, and establish a recommended program for all ownerships to help meet State goals. The State's ability to prepare State Forest Resource Plans depends upon viable mensurational systems to measure growth and yield, and predict future changes in the resources managed. "Educated guess" speculation on growth patterns and successional changes in plant communities resulting from land treatment and management decisions is often not accepted by the public and users of the land. Demand for conflicting and competing goods and services from the land will only increase in the future. Our need to "prove" that the dollars we spend in protection and management are justified by the returns expected will, most likely, intensify before future funding will be provided.

Many of the measurement and modeling systems developed during the last 10 years do an excellent job of providing specific information for a specific situation. A more general approach, with room for local modification for specific needs, could be more useful. All modeling and measurement systems should be usable and of benefit to the manager on the ground who makes and defends management decisions. The systems should be of use in establishing funding for treatment priorities, program priorities, and allocations of personnel. The measurement and

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modeling systems should be easy to modify or change as more knowledge becomes available, or different types of information are needed.

Finally, measurement and modeling systems should consider (to the extent possible) all forest species and stand conditions, and not be limited to a particular product or present definition of "commercial" forest type. Our ability to respond to quickly changing demands for products from the land will depend on how well we have assessed our resources. The risk in management decisions can be minimized only with reliable resource information.

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Contains 22 papers exploring current advances in measuring and computing growth, examining modeling systems for determining yield, and discussing new and traditional methods for determining volume of woody species.

KEYWORDS: volume, modeling, biomass, sampling

The Intermountain Research Station, headquartered in Ogden, Utah, is one of eight Forest Service Research stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

The Intermountain Station's primary area includes Montana, Idaho, Utah, Nevada, and western Wyoming. About 231 million acres, or 85 percent, of the land area in the Station territory are classified as forest and rangeland. These lands include grasslands, deserts, shrublands, alpine areas, and well-stocked forests. They supply fiber for forest industries; minerals for energy and industrial development; and water for domestic and industrial consumption. They also provide recreation opportunities for millions of visitors each year.

Several Station research units work in additional western States, or have missions that are national in scope.

Field programs and research work units of the Station are maintained in:

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Missoula, Montana (in cooperation with the University of Montana)

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